Hierarchical concepts in landscape ecology and its underlying disciplines

(the unbearable lightness of a theory?)

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(* Free after Milan Kundera's 'The unbearable lightness of being')

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ABSTRACT


The origin and specific nature of hierarchical concepts in landscape ecology and their applicability in both underlying disciplines and integrated studies are critically analysed. Most perspectives are found in process-functional hierarchies, ruled by flows of energy, matter and organisms, in spatio-temporal hierarchies and in organizational hierarchies in ecosystems. At landscape level, a universal ordering and ranking of components and processes is feasible. Applications are shown in case-studies. Critical remarks are made on the meaning and scientific use of hierarchical concepts. If a concept is strictly defined, its potential scientific contribution as an ordering principle is definitely useful. Its status as a real theory is doubted.

Keywords: climate, decision theory, geology, geomorphology, hydrology, integrated study, oceanography, pedology, systems theory

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Contents

Preface 9

Summary 11

1 Introduction 13
   1.1 Aims of this study 13
   1.2 The core business of landscape ecology 13
   1.3 Landscape ecology; goals and perspectives 15
   1.4 Landscape ecology; the role of theory 16
   1.5 Intermezzo (1): underlying disciplines and their evolution 18
   1.6 Scale as a common problem? 22

2 Hierarchical concepts 25
   2.1 Hierarchies: an introduction 25
   2.2 Hierarchies: 'Here, there and everywhere' (prelude) 25
   2.3 Intermezzo (2): systems theory and hierarchical concepts; back to basics 29
   2.4 Hierarchical principles 32
   2.5 Hierarchical principles in landscape ecology: a first rendezvous 37

3 The use of hierarchical concepts in underlying disciplines ('Handbook stuff from a hierarchical eye') 45
   3.1 Introduction 45
   3.2 Sources of energy: from the earth's interior and celestial bodies 47
   3.3 The geological system 49
   3.4 The oceanic system 53
   3.5 The atmospheric system 57
   3.6 Landforms and their dynamics 65
   3.7 Groundwater systems 72
   3.8 Soils 77
   3.9 On plants and animals; in search of operational levels for landscape research 83
   3.10 Intermediate conclusions and discussion 96

4 Hierarchical principles in integrated landscape ecology 99
   4.1 Introduction; linking, ranking and scaling 99
   4.2 Some examples of hierarchical approaches in integrated landscape ecological studies 100
   4.3 Stability and diversity of ecosystems from a hierarchical point of view? 108
      4.3.1 Introduction 108
      4.3.2 Stability-diversity relationships 109
      4.3.3 How to assess disturbances? 109
   4.4 Decision making; intermezzo (3) 112
      4.4.1 Introduction 112
      4.4.2 A hierarchical approach of decision making 113
      4.4.3 Elaboration 114
5 Concluding remarks

5.1 Introduction

5.2 Is hierarchy theory really a theory?

5.3 The need to restrict the concept?

5.4 A main division in hierarchies in landscape ecology?

5.5 Top-down or bottom-up control of ecosystems?

5.6 One or more hierarchies at work in landscapes?

5.7 Are hierarchies stable, scale-bound and do they allow predictions?

5.8 Why on earth are there hierarchies anyway?

5.9 Hierarchical concepts: a contribution to research economy?

Literature

Figures

1 The parable of the stone-cutter; traditional, told to me by Frank Veeneklaas

2 Spatio-temporal domains of landscape ecology relative to micro-scale, macro-scale and mega-scale (from: Delcourt & Delcourt, 1988)

3 Hierarchical organization in an administrative structure (from: Milsum, 1972)

4 Decision trees: from left to right minor decisions with smaller domains and importance follow from and support higher level decisions

5 Systems approach: symbols and vocabulary

6 a) Cascading systems; in a serial configuration the output of system S1 forms the input of system S2 and so on; b) Process-response systems: similar to cascading systems but changes in ‘downstream’, ‘dependent’ systems influence upstream, relatively independent systems

7 Boulding’s classification of integration levels, freely interpreted and simplified by the present author after Boulding (1956)

8 Symmetric and asymmetric relationships in hierarchies: (1) A dominates b in a unilateral relationship, (2) A dominates b, but b affects A as well in a bilateral relationship, (3) symmetric relationship in which A and B affect each other in a comparable degree

9a Hierarchical levels (from O’Neill, 1988)

9b Hierarchical levels (from Jørgensen, 1988)

10 Temporal hierarchies: larger units of time contain smaller and smaller time frames (from: Hengeveld, 1992)

11 a) Spatial hierarchy: after Beer (1967)

b) Spatial hierarchy: after Lowrance et al. (1987)

12 Organizational levels from the atom to the universe; the role of ecology (from: Haber, 1994).


14 Sources and pathways of energy driving geological processes (from: Summerfield, 1991)

15 Time (poem from Vasalis’ ‘Parken en Woestijnen’, translated from Dutch by the present author)

16 Convection cells in the earth’s interior driving tectonic plates (from: Hamblin, 1975)
17 Major tectonic plates and their movements in mm.a⁻¹ (from: Summerfield, 1991).

18a Major oceanic circulation systems (from: Strahler (1969)). Schematic map of an ocean, major currents and relative temperature

18b Major oceanic circulation systems (from: Strahler (1969)). Surface drifts and currents in January

19 Tidal ranges (from: Davies, 1972)

20 Coastal environments based on wave conditions (from: Summerfield, 1991 after Hayes, 1979 and other sources)

21 Coastal landforms in relation to tidal ranges (from: Davies, 1972)

22 Major atmospheric cells in Winter and Spring (after: Lockwood, 1979)

23 The geomorphological machine driven by atmospheric agents (from: Bloom, 1969)

24 Climatic zones and circulation (from: Forman and Godron, 1986)

25 Frontal disturbances (from: Lockwood, 1979)

26 Climatic zones according to Köppen (1931) (from: Hugget (1991))

27 Climate history (from: Eiden, 1990)

28 Rates of geological and geomorphological processes (from: Summerfield, 1991)


30 Drainage basins; the main trajectories in rivers (from: Schumm, 1988). A: 1 = collecting part, 2 = throughput, 3 = distribution zone B, C, D, E, F: subsystems

31 Hierarchies in river systems: 1st, 2nd, 3rd, 4th and 5th order streams according to the Strahler system (from: Chorley & Kennedy, 1971)

32 Groundwater systems. Smaller systems ‘floating’ on larger systems (after Tóth, 1963)

33 Groundwater systems and surface water systems hierarchically ordered (from: Stuyfzand, 1993)

34 Chemical characteristics (‘fingerprints’) of groundwater bodies in a coastal area (from: Stuyfzand, 1990)

35 Soil groups positioned after major climatic variables: evapotranspiration (y-axis) in three temperature regimes (from: Hugget, 1991 after Arkley, 1967)

36 Cross profile showing the importance of topography and groundwater quality for soils and soil characteristics (from: Kemmers, 1986). Arrows indicate upward seepage (left) and infiltration (right), Ionic ratio (a) = Ca/Ca+Cl, Ca-saturation (b) in %

37 Chemical ‘hierarchies’ represented by various mechanisms causing pH buffering in soils (from: Brink et al. after data of De Vries)

38 The role of pH determining the availability of plant nutrients (from: Bannister, 1976)

39 Classification of plan species according to their strategies towards environmental factors (from: Grime, 1979)

40 World distribution of vegetation zones (a) and its prediction using climatic variables (b) (from: Woodward & Williams, 1987)

41 Plant species number related to standing crop and soil pH (from: Grime, 1979 after data from Al-Mufti et al., 1977)

42 The flow of energy through ecosystems (from: Whittaker, 1970)
43 Losses of energy during its flow (energy in Kcal.m$^{-2}$.y$^{-1}$) (after: Odum, 1975)
44 Intricate pathways in nutrient cycling (from: Allen & Hoekstra, 1992)
45 Bird species diversity in relation to plant species diversity (a) and vegetative structure (b) (from: Krebs, 1985, after MacArthur and MacArthur, 1961)
46 Metapopulations, consisting of smaller, discrete subpopulations between which exchange of organisms can take place (from: Opdam, 1987)
47 The concept of spheres (from: Van der Maarel & Dauvellier, 1978)
48 Hierarchical model for the Dutch coastal dunes; central column: subsystems or components; left: natural processes; right: human impacts (from: Bakker et al., 1981)
49 Cause-effect relationships in the Dutch coastal dunes hierarchically ordered (from: Van der Meulen, 1990 after Bakker et al., 1981)
50 Hierarchical model for brook systems in a Pleistocene area in the Netherlands (from: Everts & De Vries, 1991)
51 Hierarchical ordering of stream habitats (from: Frissel et al., 1986). Spatial and temporal scales are indicated as well as dominant processes
52 Hierarchical ordering of environmental processes, their primary impact and subsequent chains of effects in landscape components (from: Klijn, 1994)
53 Landscape disturbances, their frequency and extent in relation to stability and variance (from: Turner, 1987)
54 Coastal features, interventions by man and responsible authorities in their respective scale domains (Delft Hydraulics, 1992)
Preface

It was a pleasure to be able to return to a subject that kept on intriguing me after the launching of our own hierarchical model for the Dutch coastal dunes in the late seventies (Bakker et al., 1979, 1981). Whereas the notion of hierarchies is much older, an increase in mainly theoretical studies within a variety of disciplines, more specifically in ecology, can be noticed. Hierarchical ‘theories’ apparently appeal to many, although the scientific appraisal varies from ‘old wine into new bottles’ to a warm welcome for a universal and promising way of thinking. It seemed worthwhile to bring together older and newer insights and to evaluate their applicability in landscape ecology.

This study tries to contribute by analysing examples from the literature pertaining to landscape ecology and underlying disciplines and by assessing where promising avenues are and where dead-end streets are. It is not meant as a ‘state-of-the-art’ of all scientific fields involved. I have tried to present interesting headlines and examples. In order to keep the contents of this study digestible for non-specialists I have also tried to avoid too much jargon and mathematical formulas in systems descriptions.

A complex terrain, such as landscape ecology and its directly related disciplines is hard to cover. Any attempt to do this depends on how one succeeds in sticking almost rigidly to headlines. I have therefore tried to give this study an eclectic character, rather than aiming at a thorough study based on extensively analysed literature. In this I rather fooled myself; to make well chosen selections demands a considerable amount of reading and to write comprehensively usually takes more time than originally assumed. Still, I am afraid the result sometimes resembles ‘the world according to the author’. During this endeavour I appreciated the mental support, useful comments and ideas from colleagues both inside and outside my own institute, each from his own background. Those who kept me on the right road were Meindert van den Berg, Freek Coeterier, Bert Harms, Peter Jungerius, Rolf Kemmers, Frans Klijn, Jan Knaapen, Ger Londo, Joop Steenvoorden, Frank Veeneklaas, Dick Verkaar, Wim de Vries, Henk Wolfert, Ies Zonneveld, Johan van Zoest.

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This study was carried out during a five months leave from management tasks at the DLO Winand Staring Centre, an opportunity kindly given to me by its directors. During this period, the management side was effectively taken over by Bert Harms.
The parable of the stone-cutter

(or how hierarchies depend on the particular point of view)

This is a story about a stone-cutter, busy with his hard labour under the burning sun. Thanks to a good fairy his dearest wish can be granted: to be the sun! Sending hot rays to all things and all living beings on earth he feels some satisfaction for his own suffering over so many years. But, he becomes frustrated by a large cloud blocking his rays and offering shadow to parts of the earth.

Changed into a large cloud, he experiences the power to shed rain and hail everywhere and to destroy crops and tease man and animals. He also enjoys causing giant torrents and moving silt, sand and gravel. However, he fails to disturb a large boulder. Realizing his inadequacy he asks for a final metamorphosis into an even larger stone. For a while he enjoys his new shape and its complete indifference to both sun and rain. Until an old colleague passes by .......!

Fig. 1 The parable of the stone-cutter, traditional, told to me by Frank Veeneklaas
Summary

Landscape ecology has to cope with a multiple complexity: a mix of abiotic and biotic systems, spatial heterogeneity and processes acting in different spatio-temporal domains. Integration of disciplinary knowledge requires unifying concepts to avoid getting entangled in huge piles of data. Hierarchical concepts or ‘theory’ seem to offer tools to identify, describe and explain ‘ordered complexity’ as encountered in landscapes.

This study starts with an overview of the origin, core business and underlying disciplines of landscape ecology. To bridge the still existing gaps between ecology (in the narrow sense) and abiotic disciplines, a common language is found in the General Systems Theory. A mutual field of interest is scale, both spatial and temporal.

What hierarchical thinking entails is explained in Chapter 2, starting with notions from daily life and extending them to scientific use. Hierarchical thinking is almost universal and widely practised evidently for its proven convenience to order and rank all kinds of phenomena from the natural, man-made and abstract world. Hierarchical concepts emerge primarily as ‘organizational tools’. Section 2.3 recalls that the General Systems Theory has been the main nursery for hierarchical thinking although its roots are much older. This theory still offers useful insights, a vocabulary and symbols for scientific use of among others hierarchical concepts. Section 2.4 elaborates upon hierarchical principles for scientific use. The awareness of asymmetric relationships, symbolizing dependence between related entities in a hierarchical structure, is pivotal. From these general principles one can distinguish several types of hierarchies: referring to natural, man-made, social and abstract phenomena and classified in spatial, temporal, nested, non-nested, process-functional and organizational hierarchies. With respect to the degree of asymmetry one can recognize almost absolute hierarchic relationships versus interrelationships with weak dominancies. It is crucial to be aware of the fact that hierarchies relate to a certain point of view, a defined application and are usually confined to a certain scale!

In landscape ecology and its various underlying disciplines, most explanatory power can be expected from process-functional hierarchies based on flow directions of energy, matter and organisms and - more specifically for living systems - organizational hierarchies describing increased complexity. Spatial and temporal hierarchies are extremely relevant as descriptive tools with which to identify spatio-temporal domains as ruled mainly by specific, process-functional hierarchies.

Chapter 3 presents examples from various disciplines belonging to the earth sciences and from ecology. Natural phenomena can be described and explained by flows of energy, matter and organisms through cascading (sub)systems or serially connected process-response (sub)systems. Flow directions and input-output relationships determine asymmetries. Within (sub)systems large and slow phenomena can be distinguished from smaller and more quickly reacting phenomena constrained by them. Self-ordering of open, abiotic systems with throughput of energy can be regarded as a sign of natural hierarchies (e.g. oceanic and atmospheric systems). In biotic systems several examples
of process-functional and organizational hierarchies are identified. Going through several components and disciplines the identification of dependent and independent variables is facilitated by geographical patterns of phenomena, offering contextual evidence.

From the reconnaissance of abiotic and biotic systems a general picture emerged of asymmetric relationships between the constituting landscape components (Climate//Geology > Geomorphology > Surface and Groundwater hydrology > Soils > Vegetation > Fauna). Relationships between components or systems are sometimes distinctly asymmetric, sometimes interdependence prevails. It was also shown that over the years the degree of dependence or independence can change gradually, as is the case between the soil system and the plant system.

Chapter 4 gives examples from hierarchical approaches in integrated landscape ecological research. Catchwords in the integration process are linking, ranking and scaling of landscape phenomena. The use of conceptual hierarchical models has, so far, been productive. Examples of application are still relatively scarce. A special challenge to operationalize hierarchic thinking is seen in landscape-ecological studies focused on stability-diversity problems in landscapes.

As landscape ecology is primarily meant to be an applied science it is worthwhile realizing that a hierarchic ordering of insights into the functioning of landscapes could offer clues for well-considered decisions. It is striking that decision 'theory' developed its own hierarchical approaches that seem to match the outcome of landscape ecological studies.

Chapter 5 offers discussion points on a somewhat philosophical level: the need to restrict a too universal concept to manageable proportions, the awareness that completely different types of hierarchies can interact synchronously in landscapes, the question of whether hierarchic constraints operate top-down or bottom-up or both, the question of whether hierarchical thinking is mainly a rediscovery of scale, the intriguing questions of why nature 'invented' hierarchical ordering anyway and even whether hierarchical thinking really is a theory or not. Although our answer to this last question is negative we conclude that hierarchical principles offer a rich and thoroughly useful conceptual framework that could add to research planning and economy.
1 Introduction

1.1 Aims of this study

The charm of landscape ecology, as an interdisciplinary or even transdisciplinary approach, is that it tries to reconcile and combine a variety of disciplines and related concepts and data. Inherent difficulties are well-known: it is difficult to avoid getting stuck in deep disciplinary tracks or sinking in the marsh of too many data from too many disciplines that prove to be hardly compatible. The quest is for unifying concepts that help to focus, organize and link data and to generalize insights for practical applications.

During the last decades, one of the more promising conceptual perspectives for this problem was launched within the realm of ecology under the heading of 'hierarchy theory' (Allen & Starr, 1982; Allen & Hoekstra, 1992; O'Neill et al., 1986; Webster, 1979). Hierarchical concepts, as we prefer to call them, claim to be a help for all sciences that are involved with complex systems, huge numbers of data and system characteristics in a broad range in scales of space and time. It has been stated that these concepts could also become a great support for landscape ecology, a field where complexity is a hallmark (Risser, 1987; Urban et al., 1987). This study tries to make a contribution to an evaluation, and possibly to an operationalization, of hierarchical thinking by successively:

i) formulating the core business of landscape ecology

ii) offering an overview of the main challenges

iii) giving a brief context of underlying disciplines

iv) offering a general picture of hierarchical concepts and a further definition of types of hierarchies that might answer landscape ecological questions

v) focusing on the possible or already realized use of hierarchical concepts in underlying disciplines (from earth sciences and ecology).

vi) presenting examples from integrated studies in landscape ecology and some current topics

vii) discussing the scientific and practical value of hierarchical concepts.

1.2 The core business of landscape ecology

"Everything in the world is connected with everything else ..., but some things are more connected than others"  
(Simon, 1973)

Landscape ecology deals with a threefold complexity appertaining to its object of study. Consider ecosystem research (in the narrow sense), aimed at complex relationships within communities, and between communities and their directly related environment albeit in homogeneous conditions; add the spatial heterogeneity in both vertical and
horizontal directions which turn areas into landscapes; then imagine the variety of abiotic and biotic patterns and processes acting on different scales in space and time, and a third source of complexity is clear. Apart from this threefold complexity in nature itself it is obvious that divergence in theories, methods, jargon and research goals in disciplines involved in landscape research is a handicap as such. No doubt landscape ecology has chosen a complicated field of study, both in a practical and a theoretical sense.

After the coining of the phrase landscape ecology (Troll, 1938; 1950; 1968; Haber, 1990), it took some time before any real activity in this field could be observed, somewhere in the late sixties and early seventies. Young as it may be, landscape ecology seems to be thriving pretty well, if the emergence of national societies and international associations as well as scientific journals (e.g. Landscape Ecology and several European journals) and handbooks are anything to go by (Leser, 1976, Vink, 1975; 1980; Naveh & Lieberman, 1984; Zonneveld & Forman, 1989; Forman & Godron, 1986; Hansen & Di Castri, 1992; Turner, 1987). This interest is not merely scientific. Many results find their way into practice, especially in planning and management.

Landscape ecology can be seen as a dynamic field where practical solutions dominate a more reflective approach aimed at a sound theoretical basis. Everyone seems content to cooperate within a loosely formulated scientific framework and from there many studies with direct practical relevance are produced. Why then bring up questions on theory? The answer is an intuitive, but certainly not a personal one (Zonneveld & Forman, 1989). We feel that the experience of a few decades has revealed a strong need for unifying concepts. First of all there is a growing awareness that dealing with landscape ecology in a really interdisciplinary manner (or even better a transdisciplinary manner in the sense of Naveh & Liebermann, 1984) demands a far better and more efficient way of handling scientific output from all kinds of disciplines. These disciplines have their own goals, theories, working scale, methods and jargon. Anyone who has participated in an interdisciplinary study will recognize this. They will also have experienced the fact that there is a related problem: a continuous threat of being choked by too much data (on patterns and processes) which then need to be combined, aggregated and simplified. The greater the number of disciplines, the greater the number of problems. [These difficulties are more marked when smart data-sampling techniques (data-recorders, remote sensing), GIS-techniques and computer facilities allow the gathering and storage of large data sets and the output from detailed modeling. These tools can easily create more data than can be managed which (consequently) creates more problems than it solves.] This phenomenon is accompanied by another: building large geographical databases and detailed submodels that have to be lined up in some way, introduce many mistakes and artefacts that may cause serious errors. Landscapes themselves may express order and coherence despite their proverbial complexity ('organized complexity'). However, the return after an analytical phase in which many disciplines participate to a coherent and orderly presentation of results is often an extremely difficult procedure. The problem is to find a channel between the Scylla of superficiality of former days and the modern Charybdis of an unmanageable pile of data from individual disciplines with too much detail and too little compatibility.

Of course, the above mentioned problems are exaggerated and need not to be considered
as invincible handicaps in the long run. We plead for an investment in unifying concepts as tools for integration. Before entering the promised land of hierarchical concepts some explanation on the landscape ecological field of research is necessary. In the next two sections we present the scientific and practical context of landscape ecology itself and some relevant aspects of underlying disciplines.

1.3 Landscape ecology; goals and perspectives

There was a time when geographers disagreed on the definition of their mutual field of interest. This theoretical pastime eventually evoked the both simple and powerful statement: 'geography is what geographers do'. In landscape ecology, such a solution seems completely redundant. Most participants are already pragmatic and feel free to work within a broadly defined framework. They define their business as being appropriate to their goals and let others do the same. This reflects a practical and sometimes opportunistic attitude. It also reflects a field of science in an early stage of development (Zonneveld & Forman, 1989). Nevertheless, amidst the variety of definitions and applications, there is common ground, from which we derive the essentials for this study instead of searching for the one and only definition that covers the lot. Some pivotal notions, referring to handbooks (Zonneveld & Forman, 1990; Hansen & Di Castri, 1992; Meentemeyer & Box, 1987; Turner, 1987; Risser, 1987; Urban et al., 1987; Forman & Godron, 1986;) are:

- landscapes are nearly always the result of both natural and man-induced processes during, nearly always, various time-scales. Landscapes can effectively be described as palimpsests (Chorley & Kennedy, 1971), patterns superimposed on each other, showing features of different eras. These legacies affect present-day and future processes.
- landscapes are changing, but changes occur at different rates, either gradually or suddenly, even catastrophically. Landscapes that are stable for a long period are almost fiction.
- nevertheless there are stabilizing forces within landscapes: disturbances are followed by a return to a former status or by a new equilibrium, both in a physico-chemical and in a biological sense.
- although landscape dynamics show many unexpected or unexplainable phenomena, there is still a large portion of predictable change such as primary or secondary succession or degradational stages.
- landscapes are mainly open systems: open to vertical influences (e.g. radiation, atmosphere), open to influences from their surroundings and internally open (exchange between patches within one landscape). Landscapes can be understood by insight into the flows of matter, energy and organisms.
- landscapes are heterogeneous, both in a vertical and horizontal direction. Vertically one can distinguish layers (atmosphere, canopy, soil, groundwater, rock etc.). Horizontally, landscapes consist of patches (or ecotopes) with typical combinations of abiotic and biotic features, which repeat themselves in a certain pattern. Between 'homogeneous' patches are boundaries which can be sharp or gradual. Boundaries are sometimes open to the exchange of matter, energy or organisms, they sometimes
act as barriers or membranes.

- landscapes are perceived as parts of the earth's surface with *a certain size but where it is difficult to give lower and upper limits*. One would agree that the size of even a large farm is insufficient to speak of a landscape, but where does the notion of a real landscape emerge? Maybe when it is considered in a geomorphological sense and, in addition, when it features a typical regime of disturbances? (See e.g. Risser, 1987). It is not easy either at the other end of the scale-spectrum. Some huge areas have more or less similar features, such as vast stretches of tundra. All this does not easily allow a standard size or scale.

The points mentioned above emerge as general landscape ecological notions. *What are the more specific application-oriented goals?*

As we deal with the more theoretical aspects in section 1.4, we can at this stage focus on the practical context: landscape ecology as an applied science. *Sustainable use* of landscapes is therefore the key word from at least two points of view (e.g. Vos & Opdam, 1992; Fresco & Kroonenberg, 1992).

Its challenge can be described in understanding the functioning of landscapes, with regard to all natural, semi-natural or cultural ecosystems. This knowledge should enable a more sensible use of landscape, taking into account the *natural carrying capacity* and should prevent abuse by man. Examples could be how to prevent land degradation by erosion leading to a loss of agricultural or other resources, how pollution of lakes causes a decline in fish production. These examples originate from a direct anthropocentric, selfish standpoint. On the other hand there is a growing (ethical) awareness of the importance of *biodiversity*. To avoid a further decline in plant and animal species and to restore nature where this is possible, more insight into the essential role of landscape patterns and processes is required.

1.4 Landscape ecology; the role of theory

'Sometimes I live in the country
sometimes I live in the town
sometimes I have a great notion
to jump in the theory and drown'
[Free after 'Good Night, Irene, Irene'
by Huddie Ledbetter & John Lomax]

Theory can be described as a framework in which accepted explanations of observed phenomena (e.g. in laws or rules), postulates, concepts and hypotheses are brought together in a logical and internally consistent order. Its role is twofold: i) to give a concise overview of what is considered as an acceptable and consistent set of explanations and ii) to act as a breeding ground for new concepts and hypotheses that still have to be tested on their applicability and validity, respectively. In short, theories are used to justify ideas and to create new ones (see: Rhoads & Thorne, 1993).

The role of theories is not always highly esteemed by all those who are actively involved in science. Chorley (1978; cited by Rhoads & Thorne) states sarcastically:
‘whenever someone mentions theory to a geomorphologist, he instinctively reaches for his auger’. Whether this is persiflage or not and whether this attitude is equally widespread within other disciplines contributing to landscape ecology is beyond the scope of this study. Our own reasoning is based upon the scientific experience that there is nothing as practical as a good theory (David Ricardo 1772-1823, see e.g. Lenz, 1994) and the conviction that landscape ecology needs theoretical support (see 1.2.). Zonneveld & Foreman (1989), in their preface, state: ‘we sense that a top priority is to develop and consolidate the core body of theory, principles and concepts’. One could safely add: ‘to run its own business in a better way’.

So, from a sound desire for theory, principles and concepts, what exactly do we need to meet future demands? Referring to 1.3, landscape ecology:

- is an applied science
- focuses on the sustainable use by man of land and landscapes and
- puts ecosystems (plant and animal life and their relevant environment) to the fore;
- deals with open systems with respect to flows of matter, energy and organisms;
- deals with systems that are vertically and horizontally heterogeneous;
- implies various scales in space and time;
- is aware of changes as intrinsic properties of landscapes;
- is more and more involved in predicting of effects;
- is interdisciplinary in that it uses many disciplines synergetically: interfacing disciplinary knowledge is a key-phrase.

It is fitting to underline a few other things. The first is that some of the aspects are certainly not the exclusive domain of landscape ecology. Traditionally geography, and especially physical geography, is familiar with heterogeneity, scales, changes, cause-effect relationships (Chorley & Kennedy, 1971; Bennet & Chorley, 1978, Wiens, 1989). Ecology on the other hand, and by definition, is aware of relationships within biotics and between abiotics and biotics. Both scientific fields have been active and effective in translating their findings into practice. All other unmentioned disciplines within these main clusters can more or less claim the same. So, where theoretical or conceptual developments in both fields (see e.g. Bennet & Chorley, 1978; Davidson, 1978; Scheidegger, 1990; Jørgensen, 1992; Roughgarden et al., 1989 ) are at stake we are convinced that a quest for a completely new theory is both undesirable and unnecessary. It would be worthwhile more to find our way in existing or promising new theories and concepts from various fields and, with top priority, to seek for unifying concepts and languages that can assist in the process of interfacing.

In this study we are focusing on hierarchical concepts. Of course there are other concepts or theories that have proven to have the ability to act as such. Ecosystems research has been pushed forward by the systems theory, thermodynamics (including the analysis of energy flows, conversion and storage; Odum, 1983) the chaos-theory (Prigogine, 1973) and recently the fractal theory (Mandelbrot, 1983, Wiens & Milne, 1989) and percolation theory (Gardner et al, 1992). The last two seem to be of pertinent importance at landscape level.

A common language enabling communication between various disciplines merits urgent
attention. We consider this to be practically within reach, which may seem a bold statement. However, analysing the way in which ecology (in the broad sense) has evolved, and the way in which several abiotic disciplines within the framework of physical geography have evolved, it is striking how much they are both influenced by the systems approach (Odum, 1971; Waterman, 1968; Morowitz, 1968; Chorley & Kennedy, 1971; Bennet & Chorley, 1978; see also 2.3). The overall impression is that there is enough common ground on this point and that our subject - hierarchical concept - could well be addressed in terms of General Systems Theory (2.3).

1.5 Intermezzo (1): underlying disciplines and their evolution

Considering the variety of disciplines that have become involved in landscape ecology, there are reasons enough to make a brief excursion to the differences between abiotic and biotic sciences. Any attempt to do this in just a few pages might lead to a caricature that neglects nuances and sometimes even some essentials. It should be realized, however, that it is not our aim to cover theoretical and conceptual developments in these fields, solely to give just enough background to understand integration problems.

Abiotic sciences or earth sciences, either considered as separate disciplines or working under the aegis of physical geography, deal with the non-living environment on or near the earth's surface. Every discipline has its own point of view and its own slice of the cake: geology, geomorphology, oceanography, hydrography, hydrology, climatology, soil physics, soil chemistry and so on. Nevertheless they have a lot in common scientifically. Processes are described and explained using a relatively small and uniform set of basic concepts or natural laws (Davidson, 1978; Bloom, 1969). Take for instance the omnipotent First and Second Law of Thermodynamics, or the awareness that all relevant forces at work can be traced back to the primary forces from the very outside of the earth (gravitational forces from sun and moon) or from inside (earth gravity), rotational forces (Coriolis) and processes governed by the supply of energy from outside (solar radiation) and inside (internal heat). All relevant processes are governed by these original forces and can be expressed as flows of matter and energy through various systems and between these systems. Disciplines describe, explain and forecast processes related to the transport of matter or several types of energy in solid matter (rock), liquids, gases (atmosphere) or compound 'three-phase' systems (soils) achieved by several agents (ice, water, wind etc.). Of special interest are forms of exchange of matter and energy at boundary layers, such as air-water or land-water and air-land interfaces.

Transport and transformation are studied on various scales in time and space, also depending on reaction times themselves. Some disciplines are used to work on large spatial and/or temporal scales (climatology, geology) whereas others have smaller scales (soil physics and soil chemistry). Most striking for disciplines dealing with large spatio-temporal frameworks is their dependence on information from the past: they reason from a postulate of pattern-process relationships such as is common practice in geology and geomorphology. For logical reasons they have to study phenomena with different ages encountered in the actual landscape in order to reconstruct changes in time. This methodology can be addressed as 'place-for-time-substitution'. Other disciplines are
far more involved in actual processes, which can be studied on a real time basis (e.g. meteorology). For most abiotic disciplines a mechanistic paradigm has prevailed which was revealed in several aspects, e.g. because reversibility of processes is assumed. This could apply to chemical reactions such as solution and precipitation of compounds or to transitions of water in liquids and vapour, or vice versa. There is also a keen interest in the importance of thresholds, values at which sudden changes can occur: erosion, sedimentation, even catastrophes. Recently, however, the mechanistic approach and the assumption of reversibility have been criticized on the basis of the Chaos Theory (Prigogine & Stengers, 1981). The non-living nature is evidently less predictable than had previously been assumed. Pathways of development are now recognized as being multiple, since minor differences in certain critical stages are decisive for the course of subsequent processes indicating bifurcation points in systems behaviour.

Some of the abiotic disciplines are working on a relatively short time-scale and have improved their insights into processes in small-scale field or laboratory experiments, leading to a causal-analytical explanation of physical or chemical processes which have allowed a sometimes detailed modeling. Great advances are being made in soil physics and soil chemistry (e.g. Richter, 1987).

In general, however, the development of many earth sciences can be categorized as being rather retrospective. For a long time studies of the genesis of phenomena (e.g. morphogenesis, pedogenesis) dominated, more than of actual or future processes, with the exception of course of meteorology and hydrology. As a result, the literature has been dominated by reconstructions of past events in order to explain the inherited landscape we perceive to day. This retrospective interest can nowadays be considered as pretty one-sided. However, the situation changed rapidly as is clearly the case in geomorphology or climatology. An increase in interest has recently been observed in large-scale and threatening developments in climatic systems and sea level behaviour. Risks to human interests seem to have triggered a second youth in these fields. A final remark with respect to the possible interface to ecology should be made. Notwithstanding notable exceptions interest from earth sciences in ecological problems has not been overwhelming for a very long time. Of course, disciplines were aware of the existence of a biosphere, but primarily because of its effects on evaporation or its role as a protective land cover or as a source of organic material in soil development, which is not the same as considering the role of abiotics for ecological goals. This is true for most disciplines and only recently have major changes in course been observed. Examples can be found in coastal dune research (Bakker et al, 1979) and riverine areas (Frissel et al., 1986; Amoros et al., 1987). Soil science, as a very practically oriented branch of science that always presented itself as involving biotics as well, can be judged as being biased in this respect: almost all attention was given to agro-ecological applications, whereas natural and semi-natural systems were almost completely neglected in most studies. A change in attitude can also be observed here, for instance by interpreting soil chemistry for ecological purposes (e.g. Ulrich, 1981) or by stressing the importance of soil organic layers as an indicative soil horizon for plant-soil interactions (Klinka et al., 1981). The same shift in attention is seen when classical soil classifications and related soil map legends are tentatively translated into ecologically relevant variables (Klijn & De Waal, 1992).
A final important feature of abiotic disciplines, relevant to landscape ecology, is their geographical attitude. As can clearly be seen in all type of studies there is a keen and logically inevitable use of geographical methods in order to get hold of their study objects: maps! This investment in surveying the whereabouts of phenomena in order to understand their origin and long-term dynamics is evident. It also made one aware of spatial variability in nature and the necessity and methods to generalize this variability. Maybe this geographical attitude is more developed than in biotic disciplines. Ecology, however, seems to come alongside quickly as 'scale is rapidly becoming a new ecological buzzword' (Wiens, 1989). The fact is that many abiotic data have so far been gathered in a more systematic and integral way than biotic data, thanks to standardized classification schemes, map legends and mapping procedures at national and international levels.

Now for the biotic disciplines. Within biology an extremely branched tree of specializations can be distinguished. To take a short-cut: many of these can be regarded as being pretty remote from landscape ecology. We refer to cell-biology and everything subcellular, but also to the level of organs or individuals. We could also neglect taxonomy (although essential for communication) and specializations focusing on extremely long time-scales (e.g. evolution biology). For our own landscape-ecological goal, levels above the individual, i.e. population, community, the ecosystem or higher are relevant. Especially those branches and approaches are important where living things are studied in relationship with their living and non-living environment.

Compared with the somewhat simple lay-out of the physical and chemical world of abiotic disciplines, where processes respond to a limited set of ‘laws’, life is extremely abundant in variety, complexity and surprises. The number of plant and animal species is overwhelming. Interrelationships between organisms are numerous and their short-term and long-term adaptations to physical or chemical constraints and opportunities are pluriform. All together this poses an unlimited reservoir of issues and scientific problems. Apart from the obvious fact that life distinguishes itself from abiotic phenomena by growth, reproduction and death, one of the most striking features is how living systems cope with all the constraints from the abiotic environment using ‘strategies’ (see 3.9).

Evidently, life succeeds to a certain degree in ‘trespassing the laws’ from physics and chemistry which seemed omnipotent. This can be understood in terms of cybernetic devices and efficient isolation techniques which enable to avoid, steer and regulate flows of matter and energy in a profitable way (Von Bertalanffy, 1950; Wiener, 1952; Boulding, 1956; Bok, 1958; Margalef, 1968; Odum, 1971). As a result, life manages to exploit these flows and maintain a state far from a thermodynamically logical situation. Even the biosphere as a whole succeeded in shifting atmospheric conditions drastically towards a thermodynamically out-of-balance situation (e.g. Lovelock, 1979).

One of the major and most powerful concepts in ecology, although subject to criticism due to its undefined scales (Allen & Hoekstra, 1992), is Tansley’s (1935) ecosystem concept. It connected life at community-level with the directly relevant abiotic environment and triggered a new era of ecological research describing and explaining biotic features in relationship to the flow of matter, energy and information. Strongly
related concepts were introduced such as food chains or food webs, nutrient cycling, trophic levels and the exchange of energy, water and minerals, whether or not by means of cycling, were also studied (e.g. Lindeman, 1942).

Other aspects, linked to the community or ecosystem level related to dynamics such as the notions on succession, either in mono-climax hypotheses (Odum, 1971) or later refined in multiple succession pathways (Horn, 1976). The role of disturbances in ecosystems received and still reveives a lot of attention. One of the major discussions, accompanied by considerable confusion, was conducted around the diversity-stability relationship. It proved that the original assumption of a simple mutual relationship could not be maintained (e.g. Van Dobben & Lowe-McConnel, 1975). Gradually, the idea gained ground that working with these concepts demanded a clear definition of time scale and spatial scales if one were not to become trapped in immense paradoxes (Klijn, 1987; Meentemeyer & Box, 1987; Allen & Hoekstra, 1992; Wiens, 1989).

The recognition of scale as an omnipresent and often crucial factor which cannot be neglected when handling most ecological concepts or issues is extremely important. This somewhat late awareness (Wiens, 1989) could be explained by the fact that the ecosystem approach was a spatio-temporally undefined concept. Its size can vary from the biosphere to the contents of a small pool. Moreover, an ecosystem was usually conceived to be a more or less homogeneous system. This approach, easily explainable for scientific proposes, was dominant for a very long time. In fact, world-wide recognition of the landscape level in ecology, including notions of scale and heterogeneity, is only recent. Allen & Hoekstra (1992), referring to American literature in the first place, state that this level had practically been ignored since the turn of the century until the nineteen-eighties. This, however is only one part of scientific reality. The Old World was undoubtedly one or two decades ahead (e.g. Haber, 1990).

Population biology and biogeography are branches of biology with a rather long history. Especially the latter seems to be witnessing a second youth. This was triggered by the awareness that part of the decline in biodiversity could be attributed to processes leading to a decrease in biotope and related (sub)population size and concurrently a strong isolation of populations by changes in landuse. These two main causes could endanger the exchange of organisms between isolated populations, the smaller ones of which being prone to extinction. This notion, originally stemming from MacArthur & Wilson (1967) and Diamond (1975) triggered much research focused on landscape fragmentation (Harris, 1984; Soulé & Wilcox, 1980; Opdam, 1987). All this can be considered as a second impulse for embracing the landscape level. It brought about thinking of fragmentation, the idea of connectivity (Schreiber, 1988), the concept of metapopulation (e.g. Opdam, 1987) and interest in the role of corridors and ecological networks.

In this short history we also should mention the involvement of abiotics in ecological studies on a higher level than edaphic factors. A distinct and inspiring study was introduced by Borman & Likens (1979), who investigated biogeochemical management at a watershed level, including responses to a major disturbance. This approach is also applicable to other scales.

At other levels, further insight into plant-soil-water relationships is also needed. One
of the main issues in Europe and elsewhere is how to order plants in ecologically relevant groups using a limited set of abiotic parameters (e.g. pH, nutrients, water quantity and water quality). After the pioneering work of Raunkiaer (1934), Iversen (1936) and Ellenberg (1974), several studies were aimed at types of ecological grouping of plants (Londo, 1988 for phreatophytes; Runhaar et al., 1987, Grime, 1979; Boutin & Keddy, 1993). Although it is akin to slave-labour to execute such work and to interpret autecological and synecological data this is crucial for a good interface between abiotics and biotics. The challenge is to give clues for a rational and practical data-reduction. One of the inspiring approaches is the clustering of organisms according to their abiotic trajectories and their life strategies as put forward by Grime (1979). The same awareness is growing with respect to the ecological grouping of animals according to their biotope demands, minimal population size, area size and dispersion abilities (Harms et al., 1991; 1993). If such approaches were eventually to lead to a sufficient coverage of organisms landscape ecologists would have an extremely good operational tool at their disposal.

When trying to derive a general picture from these sketches, it can be noticed that two very broad fields have managed to live apart for a long time, each busy with their own interests, goals and methods, whereas interfaces were scarce. Abiotics were either dominated by a retrospective interest or focused on non-ecological problems. A real inclusion of ecology is still sporadic and relatively recent. In ecology, the ecosystem concept emphasized study and conceptual evolution in homogeneous systems rather than at landscape level. The importance of heterogeneity and scale has only recently been recognized, whereas relevant abiotic processes acting indirectly and on a longer time scale are hardly incorporated. On the whole, these two fields are showing a strong tendency to be on speaking terms with each other, but altering course will demand a further change in attitude and time to gain more momentum. A common challenge is to search for working scales that fit both fields and to find common parameters that make sense in the mapping, modeling and predicting of relevant phenomena for practical purposes.

1.6 Scale as a common problem?

Scales, temporal and spatial, have the nasty habit of always and everywhere playing a role. All natural processes have their own scale domains, our observations are scale bound, our interpretations depend on scales, decisions relate to a certain time frame and spatial context (Allen & Hoekstra, 1992; Meentemeyer & Box, 1987; Wiens, 1989). If we neglect scales we are doomed to draw wrong conclusions and take short sighted decisions. Landscape ecology tries to envelop an array of phenomena, all with their own spatio-temporal domains. Awareness of scale is therefore of vital importance. Can we specify the scales of landscape ecology a bit further?

Landscape ecology tries to integrate knowledge from the so-called abiotic sciences such as climatology, geology, hydrology and pedology and the biotic sciences such as botany and zoology. A further confinement of the landscape ecological territory is however required: primarily by a restriction in scales. What is a relevant time scale? Everyone
will agree that interesting interdisciplinary studies of ecosystems in the Palaeocene as influenced by continental drift should not be part of it, although the integration of biotics and abiotics would be exemplary. We could propose a time frame that is primarily relevant for decisions varying from some decades to one century. Of course many processes in the biotic compartments have longer time horizons, e.g. the development of a complete forest community. Abiotic processes and related decisions on land management demand a much longer time frame, such as climate change or solutions for nuclear waste. The next question to be answered is how far we should go back into the past and still have the idea to do relevant things. It may resemble an escape into vagueness, but in most cases relevance will be more manifest after defining our goals and from the inherent properties of the landscapes to be studied. Recent questions on nature rehabilitation carried the conviction that reference periods could be found within a framework of between some tens to several thousands of years (Dirkx et al., 1992), others (Delcourt & Delcourt, 1988 (see Fig. 2); Birks et al., 1988) prefer to include the Holocene as a whole.

Restrictions in spatial scales maybe more difficult. Take for instance the lower limit sometimes mentioned in the literature: tens of metres to some kilometres. We believe it again depends on goals and on the size and natural grain of landscapes. Wiens & Milne (1989) show ‘from the beetle’s eye’ how very small areas can be approached as real landscapes. Very practically formulated: it should make sense. At the other end of the scale spectrum the same problem arises. Some very large areas display a characteristically repeating pattern of ecotopes and are otherwise, e.g. geologically, geomorphologically and climatologically monotonous enough to be considered as a unit.

![Fig. 2 Spatio-temporal domains of landscape ecology relative to micro-scale, macro-scale and mega-scale (from: Delcourt & Delcourt, 1988)](image)

23
In contrast other landscapes happen to be relatively small, some hundreds of hectares, such as small dune systems in an embayment in an otherwise rocky coast. *It is no use being dogmatic.* To help the process of specification we prefer to add operational criteria for decisions, which is application in land use planning or land management and nature management. Data should be as practicable as possible for decision making which has its own demands regarding relevant time horizons or spatial extent and resolution. We should add that recent problems explicitly introduce the need to include more long-term and larger scale studies for decision making (man-induced climatic changes, sea level rise, large scale pollution from the atmosphere) than we have been used to. Following developments in world economics, in environmental and nature conservation issues, it appears that a process of upscaling is taking place, accompanied by an upscaling administration that must inevitably be followed by scientific approaches (e.g. Turner & Gardner, 1991).
2 Hierarchical concepts

2.1 Hierarchies: an introduction

Hierarchy is a deceptive concept, familiar and simple, and at the same time abstract or multi-interpretable. We think it best to follow a 'spiralling' approach in order to focus the issue. Firstly we present examples from daily life to illustrate the origin and widespread use of hierarchy in our man-made world and our efforts to order and rank observations of natural phenomena (2.2). After this prelude we will try to retrace the scientific concept of hierarchy by returning to the General Systems Theory (2.3). This theory proves to be an important nursery for a hierarchical way of thinking. Neither systems thinking nor hierarchic thinking are very young. Hierarchic thinking is by no means a modern accomplishment, Webster (1979), Allen & Starr (1982) and O'Neill (1989) refer to ancient Greek writers. Systems thinking as such has its roots in Aristotle's philosophy (Von Bertalanffy, 1972) and has made its revival in relatively modern holistic philosophies such as that of Smuts (1926/1936), Teilhard de Chardin (1959) and Koestler (1967).

In 2.4 we will try to formulate basic principles and distinguish hierarchies according to their respective leading principles.

There has been an acceleration in thinking and writing on hierarchies over the last decades, from an array of disciplines. This includes abiotic fields but especially ecology (Allen & Starr, 1982; O'Neill et al., 1986; Webster, 1979; Allen & Hoekstra, 1992). It is considered to be worthwhile to broaden the scope to organization theory or decision making as well. Hierarchy is, in the first place, an organizational concept, a second reason is that landscape ecology is an applied science trying to increase knowledge in order to support decisions in land use planning and in the management of landscapes.

2.2 Hierarchies: 'Here, there and everywhere' (prelude)

'There, there and everywhere'
[Song title by John Lennon & Paul McCartney]

The term hierarchy originates from the world of religion and ecclesiastical organizations (Von Bertalanffy, 1972; Milsum, 1972). According to Webster's Dictionary it referred to 'a ruling body of clergy organized into orders of ranks each subordinate to the one above it'. This principle of ranking received a more general purport by indicating organizations with grades orders, or classes ranked one above another (Oxford English Dictionary). This section aims to give examples from daily life to show the broad scope of the term hierarchy and to illustrate at the same time the gradations in meaning.

Broadly speaking hierarchy can be viewed as a notion of how people, living and non-living things or abstract phenomena are organized, based on their position relative to
each other. This notion includes the idea of inequality or asymmetry in relationships in the sense that one unit is more or less subordinate to another. When units are ordered and ranked accordingly levels emerge. Within a level, units have equal or symmetric relationships or stated in a different way: they are not subordinate to each other. Higher levels rule or constrain and often but not necessarily contain lower levels. The behaviour or performance of a certain level can be explained partly by the functioning of units in the lower level. The number of units increases downwards, while these units are smaller, less complex and acting on a shorter time scale. This is the basic principle, almost too simple for words.

Hierarchies can be recognized almost everywhere. Closely related to the etymology of the word is the example of the Roman-Catholic Church where a distinct command structure can be recognized (Pope > Cardinal > Bishop > Priest > Chaplain). Similar constructions are found in armies (General > Lieutenant > Sergeant.... > Soldier) as mentioned by Webster (1979). This command structure could also be indicated as a 'pecking order'. More generally we find the same lay-out in organizations in the private and public domain (Fig. 3), such as companies and governmental bodies (Nation > Province > Municipality). Higher levels, represented by persons, or groups of persons, have the power to decide upon lower levels or at least to give a set of constraints. We are familiar with these forms of hierarchy: the more severe examples of command structures will still cause some of us to have an allergic reaction. More democratically organized hierarchies with less severe constraints are experienced as being more harmless, which is sometimes felt to be synonymous with less effective or just downright inert. It is evident that the first category of hierarchies is a top-down structure ('command structure'), whereas the second category (representative organs) derives its power originally from a bottom-up process.

The above explanations of hierarchies have remained within close reach of the original meaning of the word. The term hierarchy however has evolved to a concept with a much broader spectrum. Hierarchical approaches have been widely used to organize or order and rank all kinds of units. Take for instance our man-made material world. We can recognize a vast array of distribution systems, devised, constructed and used by man. Smaller units together forming a somewhat larger unit and so on have proven capabilities. Examples are systems for water supply, energy supply (gas or electricity) or the distribution of information (e.g. telephone). Infrastructure, meant for the transport of goods or persons,

![Diagram of a typical administrative hierarchy.](from: Milsum, 1972)
is usually organized in a hierarchical manner analogous to other distribution systems: main supply systems branching into finer and finer systems in order to move things destination. The inverse can also be found, for instance a drainage network where small ditches collect and transport surplus water to wider ditches, canals etc. Although many of the older systems may be partly ‘organically’ grown, a considerable part has been designed according to a hierarchical notion ‘avant la lettre’. Numerous examples could be derived from machines, in devices that are in daily use. Readers are referred to the vivid description of a motor cycle as a hierarchical structure as well as the proper (i.e. hierarchical) way to detect any defaults, by Robert Pirsig (1974) in ‘Zen and the art of motor cycle maintenance’.

Hierarchical approaches can also be found in completely different fields, equally man-made, but belonging to the abstract world. We use them as tools to organize abstract units. The contents of a book clearly exhibit hierarchical thinking (book > part > chapter > section > paragraph, etc.). One could even distinguish lower levels: sentences and, within sentences, groups of words that can be approached hierarchically (Koestler, 1967; Chomski, 1957). In the opposite direction, starting from the book level - at a higher level, library systems show a structure strictly organized according to hierarchical rules.

Looking at the relatively young development of computer hardware, software and the noble art of modeling, it is striking how their architecture is based almost exclusively on hierarchic thinking (Allen & Starr, 1982). In short, at least in the man-made world, either concrete or abstract, hierarchical systems can be found almost everywhere. The more you look, the more examples emerge. Hierarchies seem to be convenient ways of ordering and ranking our possessions and thoughts. In addition, referring to examples from organizations, they help to structure our decisions. We are all accustomed to hierarchical decision making, often even unconsciously, in our own private lives. Decisions on holidays for example are made starting from global preferences for type of holiday, season and country, before deciding on details such as camping equipment or clothes. Decision making, also in more complex affairs, follows the same hierarchical principles in a more rational and sophisticated way, at least we hope so. Decision trees are the visual expression of a hierarchical process! (Fig. 4)

We could extend our view gradually to another category, namely the way we organize our observations (and ideas) of the surrounding world. As the human mind has its limitations in memory capacity and in understanding complex matters, tools for a more convenient storage and retrieval are helpful. Equally important, we need simple, abstract,
vehicles with which to communicate, and for that reason as well tools for ordering and ranking our observations and assumptions or conclusions are welcomed. Hierarchical approaches have proven capabilities to support us. Take for instance our perception of time. Time has been classified hierarchically (centuries, years, months, weeks, days, hours, minutes, seconds). Space could also be approached in such a way, by identifying small entities, forming larger entities and so on. In a comparable way we can structure our knowledge of plant or animal life. Familiar and famous examples can be seen in the way Linnaeus ordered and ranked plant species in a hierarchical system, constructing taxa from species clustered in higher taxonomic levels (genus, family and so on). Countless other systems are organized analogously. Every branch of science knows typologies, classifications or taxonomies using several hierarchic levels. As our objective is a convenient storage and retrieval of data, these classifications are extremely useful from a bookkeeper's point of view. There is one important characteristic of all these hierarchies: they are mental constructs to support us when working with natural phenomena that are not necessarily organized hierarchically by design, by evolution or by accident.

But, and here we meet a crucial point in all scientific hierarchical approaches, lots of natural phenomena are perceived by man as being hierarchically structured 'in se, by nature itself!' The way subatomic particles are united in an atomic structure, atoms in a molecular structure, molecules in a crystalline order can easily be seen and explained in hierarchical terms. The same is true in the structures of the macrocosmos. Some authors are convinced that hierarchical organization in nature is universal and omnipresent. As remarked by Bertalanffy (1950): 'reality, in the modern conception, appears a tremendous hierarchical order of organized entities, leading in superposition of many levels ...'. Milsum (1972), dealing with living systems is quite pertinent: '.... a hierarchical structure was accepted almost universally as the necessary and sufficient basis for all living systems ....'. A comparable opinion comes from the physical geographers Chorley & Kennedy (1971): 'We can, therefore consider that 'reality' is a hierarchy of organized systems ...' or from Mesarović et al. (1970): 'Existence of hierarchies in nature has been discussed by too many, too often, adding too little to what was already known: namely that the hierarchical arrangement does exist'. Other authors however are reluctant to accept such a grand design and suggest that our minds are strongly inclined to arrange observations in a hierarchical manner. The latter is a psychological explanation referring to a deeply rooted desire to bring order in our mental work. To quote Webster (1979): 'whether Nature is truly organized hierarchically is moot. Man's perception of nature is hierarchical' or Woodmansee (1989): 'It is important to remember, however, that nature is not simply a grand hierarchy of systems at various levels of organization; rather, nature simply is'.

We do not see much profit in getting entangled in this philosophical debate, because the latter statements are i) universal for nearly all scientific approaches of natural phenomena and ii) cannot be regarded as a major objection to using hierarchical concepts in a proper way. We sidestep the problem by stating that the natural 'organization' of nature at least has a strong resemblance to hierarchical ordering and that this fits our psychological preoccupations or needs very well. Attempts from science to order natural phenomena hierarchically should be judged upon their practical value in the first place (see also Allen & Starr, 1982).
So much for the examples, hoping they help to illustrate the general idea. From the examples it becomes clear that hierarchical notions, their meanings and applications seem to be almost unlimited. We can conclude that the hierarchy concept is evidently universal, hardly a prerogative of scientists and seemingly almost too simple for words. Next, the widespread use as a tool for organizing things or abstract units reflects its practical meaning: convenience! The central notion is that of an organizational concept. However, when something is so universal and widely used in daily life, existing before and outside any scientific framework, we could perhaps consider it primarily as common sense. Maybe hierarchy is scientifically rephrased common sense? Or to quote from a favourite song by Peggy Lee: 'Is that all there is?'. It is evident that, in order to accomplish an operationalization of these concepts in landscape ecology, we need to analyse, order and rank hierarchies themselves and be selective in what is scientifically useful! We will address this problem in 2.4, but before doing so it is necessary to give some credit to the General Systems Theory that cradled hierarchical thinking.

2.3 Intermezzo (2): systems theory and hierarchical concepts; back to basics

To proclaim at an early stage a scientific approach as 'the skeleton of science' (Boulding, 1950) exhibits pure bravado or a prophetic gift to envisage its future importance. Since the appearance of the key publications by Von Bertalanffy (1945; 1950) and Boulding (1950) science historians can now safely conclude that it is a prophetic gift. The General Systems Theory is so widely accepted and implanted in all branches of science that even its founders have been surprised (Von Bertalanffy, 1972). This process still seems to be continuing. The way of thinking promoted by the systems theory has been internalized in most scientific approaches. Maybe to such a degree that it is easily forgotten what was stated by the founders on certain popular themes of today. We explicitly refer to hierarchy 'theory', for this could be considered to be a direct descendant of the General Systems Theory (Simon, 1962; O'Neill, 1989).

Although we feel obliged to return to the basics of the General Systems Theory this excursion should be restricted to some essentials insofar they are relevant to the explanation, description and possible use of hierarchical concepts. Eight items are thought to be essential:

1. A system is 'any structured set of objects and/or attributes, together with the relationships between them. A whole, which is compounded of many parts, - an ensemble of attributes' (Chorley & Kennedy, 1971). Directly connected to this concept is the notion of 'Gestalt', actually the adage of holism since Aristotle, that the whole is more than the sum of the constituent parts: thanks to the interaction of these parts the system reveals new properties or performances. These are called emergent properties (Miller, 1975) or macroscopic properties (Margalef, 1968).
2. Systems and their relationships and the characteristics of flows and other functions can be analysed and visualized by the use of a common package of terms and symbols and the use of mathematics to describe their functions (see Fig. 5).

3. Systems can be regarded as units with more or less clear boundaries (e.g., Davidson, 1978; Bennett & Chorley, 1978). Boundaries can be distinguished with respect to other systems or the environment that envelops and influences systems.

4. All systems and their behaviour and relationships can be analysed and understood by their role in the flows, storage, and transformation of matter, energy or information. For convenience, systems are considered as boxes, flows to and from the environment such as input and output, and internal processes such as throughput, storage or transformation. A distinction in system types is introduced related to their connections with the outside world. Open systems exchange matter and energy (and information), closed systems exchange only energy (and information). Systems react to flows and changes from outside (driving forces or forcing functions). Their dependence on these external, ‘independent’ decision-variables, is shown by a change in state variables. Other variables act as filters, influencing input or output and therefore they are also decision variables. If these can be manipulated by man to influence systems behaviour one can speak of key variables. The distinction between independent variables and dependent variables is of major importance when describing and explaining hierarchical phenomena.

5. Systems can be considered to be composed from smaller subsystems, that envelop smaller subsystems and so on (Koestler, 1967). In the opposite direction, systems form part of larger units and so on. This is in fact a central hierarchical concept, referring to the so-called nested systems or nested hierarchies.
6. The notion that systems can be arranged in series, where the output of one system (flow of matter-, energy, or information) acts as the input for the next system and so on. This serial configuration is called a cascading system (Fig. 6a) (Chorley & Kennedy, 1971). If there is feedback, either positive or negative from (relatively) dependent systems to relatively independent systems more 'upstream' in flow direction, one can speak of process-response systems (see also Fig. 6b). These functional relationships act as an important feature for so-called process-functional hierarchical phenomena (see 2.4.).

7. Systems can be classified according to their complexity or degree (or level) of integration of entities that allow specific performance. This feature can be understood in terms of cybernetic properties such as feedback. Boulding (1950) designed a useful classification based on functional criteria, which is shown in Fig. 7. This was presented as a hierarchy of systems, based on an increasing level of integration (see 2.4).

8. Generally, systems are considered to be more or less stable units with an unlimited lifetime. Living systems or higher integration levels that contain living subsystems such as ecosystems, are however composed of attributes subject to all kinds of change. Although living systems are generally known for their tendency to maintain homeostasis, the ecosystem contents exhibit a complete renewal and metamorphosis as may be clear in ecosystem development.
2.4 Hierarchical principles

Some general ideas on hierarchies have loomed up from the two preceding sections. In this section we will try to elaborate these ideas in order to define a foundation for scientific operationalization. As explained in the 'Prelude' hierarchies are abundant in common parlance and are pluriform. They all seem to have their own characteristics in addition to some shared properties. So the need arises to order and to rank them! We will do this by identifying major principles.

Asymmetry in relationships
The first and outstanding principle of hierarchies dealt with so far is that they are based on inequality or asymmetry in relationships. Levels in hierarchy - often visualized as discrete layers - communicate. They are 'vertically' related in one or another way. Units or members of a level show asymmetric relationships with the next higher and next lower levels. Asymmetric relationships do not occur within one level: units or members
are related, but their relationships are equal or symmetrical. One could describe these properties as follows \( B > a \text{ respectively } a1 = a2 \), where \( B \) is a member of the higher level and \( a1 \) and \( a2 \) are members of the same (lower) level. At this stage we will use this very broad concept of asymmetry in relationships: in size (bigger units containing smaller ones), with respect to relationships in the flow of matter, energy or information ('downstream is more dependent on upstream units'), at organizational level ('higher levels are more integrated or organized than lower levels') or whatever asymmetry should be relevant. This poses the question of which criteria should be used for ordering and ranking phenomena: what exactly are the asymmetries upon which hierarchic levels should be based?

We should stress once more that defining criteria not only demands insight into how nature functions, but it also presupposes an idea of our main interest and ultimate goal. In view of the variety in hierarchies (and related dependencies) they cannot be handled as one-dimensional, unambiguous and absolute. We must define our goals before deciding upon what units are to be attributed to a certain level. Take for instance the previously mentioned classification of plant taxa according to Linnaeus. Subspecies belong to one species (higher level). At species level all plants are equal but they belong to a higher taxon (genus). This is taxonomic ordering, which solves our 'bookkeeping problem' and is also very helpful when explaining evolution. In ecology, however, it is far more useful to look for other types of asymmetries, such as host-parasite or prey-predator relationships or differences in competitive power. Such asymmetries could well be completely different from taxonomic ordering principles.

Examples from daily life can illustrate the same notion: households are normally dependent on distribution systems for electricity or water. In this respect all households can be classified and ranked accordingly into one level. Relationships between these units are equal or symmetric, since no one is more dependent on a neighbour than the other way around. Of course this is not necessarily true for other aspects of life. We may rent our house from the neighbour who, in turn, could be employed by another neighbour. The message is clear: asymmetries in relationships need to be identified and selected explicitly before we can decide to order and rank units into a meaningful hierarchy.
Emergent properties

The second principle is based upon the notion that, once levels have been tentatively distinguished, higher levels should show distinct properties not found in lower levels. This refers to the emergent properties (Miller, 1975) mentioned earlier or the so-called macroscopic properties in the sense of Margalef (1968). Emergent properties can be understood and explained partly on the basis of our knowledge about the constituent parts of the lower level, but not fully (Allen & Starr, 1982). Some of the emergent properties can indeed be derived from lower level properties, some of them can be explained by looking more critically at the specific configuration of the constituents, but some properties will always surprise us. One never explains the behaviour of a combustion engine by looking smartly at the different parts or groups of parts. The same is true for the behaviour of a herd of animals (population dynamics, defense strategies, social order, migration characteristics) that cannot fully be understood by studying individual properties alone. It is very tempting to seek explanations in special configurational or organizational features and, strongly related, in cybernetic performances found in more complex systems and not in the simpler ones. Another part of the explanation refers to scale itself: on a higher spatial scale we sometimes observe a change in the relative importance of (physical) laws. Take for instance the behaviour of water particles at the molecular level where viscosity is an important feature compared with the scale of oceans where the Coriolis effect affects ocean currents (Steele, 1989). Some features directly relate to increased numbers or volumes, explaining slow behaviour, inertia or average behaviour. We abstain from further causal excursions at this stage and - accepting the existence of emerging properties - point to the expectation that scientific approaches should focus on the recognition of these emergent properties in order to present a concise picture of systems behaviour related to specific different levels. Awareness of this principle could theoretically add to economy of research and presentation of results.

Constraints

The third principle is that higher levels constrain the behaviour of lower levels. In other words they limit the degrees of freedom of lower level-units. Thus, higher levels give context and boundary conditions (or constraints) for lower levels. This feature is often regarded as the essence of hierarchies (O’Neill et al., 1986; Allen & Starr, 1982). Examples are obvious: command structures exhibit constraints for the lower ranked. Distribution systems set limits to volumes and rates of the use of gas or electricity. Ecosystem-dynamics, e.g. interspecific competition or prey-predator relationships set limits to growth rates or numbers of individuals in a population, social control mechanisms can regulate individual behaviour. A logical consequence is that any change in higher level characteristics causes a change in constraints for the lower level, which influences the behaviour of its units, and so on descending the hierarchical ladder.

Reaction time

A fourth principle, in our opinion connected to the second and third, is that higher levels tend to react more slowly than lower levels. Generally, there is an increase in reaction time going upwards through the levels. Many authors stress the fact that differences in process rates are the main indicators of distinct levels (O’Neill, 1988).
Containment
A fifth principle is related to the nested systems, which are a subcategory of hierarchical systems. In nested systems the smaller units of lower levels belong 'physically' to the higher level units. Higher levels contain lower level units which are evidently smaller and more numerous. Examples are found in organizations such as armies, companies, research institutes etc. Individuals belong to departments, that belong to divisions, that belong to the organization. To describe this one could count the number of units within a level ('span') and the number of levels ('depth'), Koestler, 1967). Ratios in size or numbers of level units in man-made systems vary, but there is evidently an awareness of some golden rules. In management systems a factor of 10 is sometimes mentioned (Milsum, 1972). Too many layers or levels in an organization, one-over-one hierarchies and too many members within one unit are all impracticable features that we have learned to avoid.

It is very tempting to observe natural systems in the same manner: why are they organized - at least seemingly - into hierarchies, how many levels do we recognize, are there any golden rules in nature and what mechanisms can be considered as explanations? (see also Chapter 5).

Indicators
A sixth principle is that higher levels and their performance in a hierarchy can often be characterized by fewer and simpler indicators. There is evidently no need to combine all knowledge on underlying levels in order to reach an adequate picture of the behaviour of a certain level. It is sometimes more worthwhile to analyse higher level constraints. This is really interesting for research, because it seems to add to research economy in the first place and offers good advice not to start at a too detailed level. Most features mentioned above are visualized in Figures 9a en 9b.

![Diagram of Hierarchical Levels](from O'Neill, 1988)
Towards a classification

Starting from the general principle of asymmetric relationships it can be concluded that
hierarchy is both a popular metaphor and a term with an extremely broad spectrum.
Before assessing its possible contribution to landscape ecology and underlying
disciplines it is worthwhile presenting a classification after:

The type of systems:
- natural systems (living and non-living)
- man-made systems (our technical world)
- social systems (social organization)
- abstract systems (e.g. taxonomies)

The question of containment:
- nested systems (smaller entities belong structurally/volumetrically to larger entities
  at a higher level)
- non-nested systems

Time and space (refers to nested systems!):
- spatial hierarchies (large spatial units contain smaller spatial units)
- temporal hierarchies (larger time units contain smaller time units)

The causes of dependences between hierarchic levels:
- 'downstream' is process-functionally more dependent than 'upstream' compartments
  with respect to transport of energy, matter or information.
- organizational hierarchies: more complexity, based upon more connections between
  constituent components causes i) specific behaviour of the complex unit and ii)
  constraints from the whole towards those components.

The degree in asymmetry in relationships between dependent and independent:
- absolute hierarchies: the relationship is a one-way street (the independent unit is not
influenced by the dependent unit whatsoever). This refers to cascading systems. Relative hierarchies: there is an ('two-way-street') interrelationship in which the relatively dependent unit also affects the relatively independent unit (this refers to process-response systems in a serial configuration).

2.5 Hierarchical principles in landscape ecology: a first rendezvous

Although hierarchical concepts seem to appeal to many ecologists it is commonly felt that a real operational use still lies beyond the horizon. To quote O'Neill (1988): 'as a result ecologists generally have a positive reaction to hierarchy theory ... But, ...ecologists have been frustrated by the lack of application of the concepts ...'. What is true for ecologists from a somewhat longer period of experience is certainly true for landscape ecologists chewing over these ideas which instinctively gained their sympathy. Urban et al. (1987) state that: 'hierarchy theory is conceptually appropriate to landscape ecology ..., but ... we have started very little that is actually novel, we have merely rephrased familiar notions in terms of patterns at characteristic scales'. This conclusion has a striking similarity to the one with which we ended section 2.3.

So there seems to be a sad feeling about the gap between benevolent expectations and recalcitrant practice. This gap should be analysed further from the following positions:
- with regard to the many hierarchies described above, it is unproductive to look for the one and only hierarchy fitting all relevant phenomena in landscapes. Patterns and processes, cause-effect relationships, biotic as well as abiotic, a variety of scales in time and space, prohibit attempts to forge them into one all-purpose (see e.g. O'Neill, 1988). One should be prepared for an outcome that several hierarchically operating mechanisms operate synchronously in the same landscape.
- there are large differences between landscapes in both nature and scale of patterns and processes. Absolute solutions fitting all landscapes and all scales should, frankly, be mistrusted!
- A sensible and practical use of hierarchical concepts is closely related to the proposed application. Practice should direct choice.

Within the realm of (landscape) ecology the scope of observation, or the 'window' can vary from the individual organism in a homogeneous environment to the entire biosphere. This is visualized in the more or less classical ladder of organizational levels of nature (from Haber, 1994). For landscape ecology the scale and integration level seem to be an 'a priori': the landscape. However, practising landscape ecology continuously demands a keen awareness of more levels than the next higher or the next lower as indicated by the ladder. Hierarchy theory should not lead to dogmatism!

The main problem for (landscape) ecology is that it has to struggle with (too) many variables and (too) many interactions between entities so that one cannot see the wood for the trees. Complexity and large numbers of entities manifest themselves at lower levels of organization and the problem only seems to increase when climbing to higher levels. Ordering and reducting of data by lumping seems the only way out. The question is how to manage this in a rational, meaningful and convenient way.
Hierarchies as a tool?

Data ordering and reduction, to stress this again, must make sense. Here we encounter the claims of hierarchic concepts to give added value. Several approaches are at our disposal when handling abiotic and ecological phenomena (2.5; Arnolds (1990): i) (abstract) taxonomic or syntaxonomic hierarchies, ii) evolutionary or other temporal hierarchies, iii) spatial hierarchies iv) hierarchies based on integration levels and v) hierarchies based on matter and energy flows and exchange (e.g. food relationships).

**Taxonomic and syntaxonomic hierarchies**: a widely accepted and familiar method is achieved by the lumping and splitting of taxa using a strict hierarchical structure (species < genus < family < ... < vegetable kingdom). This taxonomy is mainly based on species characteristics in morphology and especially reproductive organs. Somewhat related in architecture are attempts to cluster syntaxonomical units such as is done in vegetation science or plant sociology, in which plant (sub)associations are units at the basic level, clustered to higher syntaxonomical levels (association < ... < class < order). As this clustering usually relates to a common set of environmental conditions it also bears the seed of a functional classification.

Taxonomies are also found in abiotic disciplines, e.g. in soil classification (‘Soil Taxonomy’). The main thing is that classification systems are organized so that higher level units encompass lower level units. How this is done may differ considerably depending on goals and classification criteria (e.g. pedogenetic, morphometric). Where biological species are relatively (!) easy to isolate as natural units, most abiotic phenomena exhibit gradual transitions that impede clear-cut natural classifications.

**Temporal hierarchies** encompass classification structures of smaller time units clustered into larger units and so on. **Evolutionary hierarchies** are used to reconstruct the origin of species, showing the ‘birth’ of species from their evolutionary ancestors during time as a delicately branched pattern, starting with primitive life forms at the root and ending with biodiversity of (sub)recent times. Other disciplines, notably geology, also use hierarchical classifications of time to delineate relevant geological temporal units (see Fig. 10). The importance of these hierarchical concepts for applied landscape ecology is limited or very indirect.

**Spatial hierarchies** are found in most abiotic landscape disciplines and plant and animal geography. Attempts to map patterns of, geological, geomorphological features, soils, plant and animal distribution made it necessary to distinguish smaller spatial units starting with more or less homogeneous units, that can be combined in larger units, which make up still larger units, showing increasing heterogeneity. This is an example of a spatially nested approach: larger geographical units contain smaller units (Fig. 11a, b). This could also be addressed as an aggregational hierarchy. The main thing in aggregation procedures is to find a way of lumping smaller units into a more complex larger unit that makes sense, e.g. by taking into account a common age or genesis of subunits or focusing on functional relationships (transport of matter, energy or organisms) between patches. A different approach is to start top-down by dividing large, complex geographical units into smaller units (see Zonneveld, 1994 for discussion). Without functional criteria, aggregations have limited value other than data reduction and geographical simplification. Combining smaller units into larger, more compound
Fig. 10 Temporal hierarchies: larger units of time contain smaller and smaller time frames (from: Hengeveld, 1992)
Spatial units demands a conscious choice of differentiating criteria that are characteristic for each aggregational level and give added value to it. Biogeographical factors relating to the availability of species tend to have more explanatory power on higher scales (e.g. biogeographical zones), the macroclimate is also decisive on a larger scale, but on a local scale other factors, for instance competition, prove to be decisive.

Another type of hierarchy is based on an ordering of integration (or organizational levels). This point of view is essentially based on 'classical' notions on increasing complexity (increasing the number of relationships between organisms, feedback mechanisms and related emergent properties/performances), and more or less explicitly on size and scale of units going from the lowest to the highest level. Several authors, from Boulding (1956) to Haber (1994) have presented such a 'classical' hierarchy. From the last mentioned author we chose the example shown in Fig. 12. This is a 'nested hierarchy', meaning that lower level units volumetrically (i.e. spatially) and structurally belong to the higher level units (e.g. Rowe, 1956). As emphasised by several authors the size and life-span and reaction time of units generally increase towards higher levels.
However, this is not an absolute law; populations or communities of small organisms can be much smaller than the size of an organ of a large mammal (Allen & Hoekstra, 1992). This hierarchical ordering is consequently somewhat abstract: it appeals to our perception of smaller units which are functionally related to form a larger unit, but more precise scale indications are lacking. Causally oriented explanations of how higher levels constrain lower level units or how emergent properties on higher levels originate are sometimes far from simple. Notwithstanding problems in explaining the phenomena, the 'ladder of levels' is very useful to recognize the position of the focal level relative to the next-higher and next-lower levels. As indicated in Fig. 12, ecology deals with the trajectory of levels between organism and biosphere. For landscape ecology the realm is more or less the same as for ecology in the broad sense, be it with some extensions to the higher levels of the earth system and occasionally the solar system to understand the major constraints playing at these levels.
The process-functional hierarchical approach - evidently more causally oriented than all the other hierarchical approaches - is based on the flow and exchange of matter, energy and organisms (see section 2.3).
This entrance for ordering landscape ecological phenomena is what maybe appeals most of all as it offers some explanation to relative dependence and independence in biological systems, ecosystems and landscapes. It could also support other hierarchical approaches. Insight into energy and matter flows inside and between the abiotic and biotic compartments helps us to understand functional relationships in general and support adequate taxonomies, spatial hierarchies, etc.

Once more it can be concluded from the above that hierarchical concepts seem to be very patient stuff with which to envelop landscape ecological phenomena. It can also be stated that landscape ecology cannot be based exclusively on one type of hierarchy. From our evaluation it may have become clear that our choice is to focus on:

**Process-functional hierarchies based upon flow directions**
The essence is the relative position of systems in flows of energy, matter and information. Systems can be ranked according to their dependence on other systems for their input. For landscape ecology, flow of organisms can be regarded as a special case of information flow (next to matter and energy flow).

**Hierarchies in complexity or organizational properties**
The essence is that units can be ordered and ranked upon their complexity insofar they are related to cybernetic or regulating properties in the sense of Bouldings scheme (Fig. 7). This is a common concept in biology and also in organization theory and it emphasizes the role of information flows.

**Temporal and spatial hierarchies**
Other hierarchies (temporal and spatial) are essentially descriptive but nevertheless indispensable. They can give contextual evidence to functional hierarchies and - inversely - insight into functional hierarchies could help improve these other hierarchical approaches by offering clues for meaningful units.
3 The use of hierarchical concepts in underlying disciplines ('Handbook stuff from a hierarchical eye')

3.1 Introduction

Landscape ecology thrives on underlying disciplines, both from the realm of earth sciences and from the various branches of ecology. Before entering the full complexity of landscapes in order to retrieve hierarchical phenomena or concepts from an interdisciplinary approach it is considered worthwhile to explore the disciplinary fields as such. This chapter presents examples. It proved necessary to include handbook stuff which, although familiar to specialists, would be relevant for other readers. Each section offers an introductory statement, a systems description that includes the main driving forces and decision variables for systems behaviour, relevant scale domains in space and time and an indication of how systems influence other, dependent systems. The above can be explained as follows:

- When linking abiotic and/or biotic systems, the direction of potential flows of matter and energy (and information) between and through systems was considered (2.5) crucial. Flow directions of matter and energy are helpful in deciding what system is dependent on another system. This corresponds with the idea of functional hierarchies between cascading or process-response systems. Our approach puts this principle to the fore. Admittedly, there are many cases where flows of matter follow cyclic routes and causal relationships are therefore difficult to define. In most cases however the analysis of the flows of energy and the various points in the route, where the energy dissipates or is stored (sinks), can help to distinguish between independent and dependent systems. Energy flows direct flows of matter in nearly all cases (Odum, 1983).

- Systems and related phenomena in landscapes generally have a certain range in spatial extent, and their behaviour (dynamics, lifetime) fits within a certain time frame. They can therefore be regarded in their specific spatio-temporal positioning. It is helpful to present systems or related phenomena relative to others in simple x-y-diagrams with (logarithmic) scales for time and space (e.g. Odum, 1983; Delcourt & Delcourt, 1988; Hugget, 1991; see Fig. 13; Urban et al., 1987, O'Neill, 1986, 1988). This helps i) to arrange issues in an order that corresponds with the notions of spatial and temporal hierarchies, ii) to distinguish phenomena by their specific spatio-temporal domain within the same material system iii) to realize that phenomena in various components of landscapes are either in very different or in comparable domains of temporal and spatial scales and iv) to separate relevant from irrelevant phenomena judged upon their scale-domains relative to the landscape-ecologically relevant domains.

- For our purpose it is assumed that large-scale systems are generally relatively independent and set constraints towards the smaller scaled, quickly responding, relatively dependent systems. The larger systems tend to be more sluggish. It is evident that large-scale, slowly moving systems such as geological units responding to plate tectonics belong to the first category. Quickly reacting systems, such as animal populations with a small areal extent are evidently examples of the second category. There are certainly exceptions to this rule, as will be clarified later in this Chapter.
- **Complexity or organizational level** is a property strongly connected to biological or mixed abiotic/biotic systems. In these systems, cybernetic properties are important in regulating and conducting flows of energy and matter through the various compartments of the systems. Each organizational level can be characterized by specific cybernetic properties (Boulding, 1956).

- Where the analysis of flows of matter and energy often yields insufficient and ambiguous data it is relevant to use **contextual evidence** which can support presumptions on relative independences and dependences of natural phenomena. We consider sound comparisons of geographic patterns of landscape features to be a good aid. The geographical distribution of climatic variables and dominant vegetation types on earth indicates such relationships. Of course this is a **correlative approach rather than a causal-analytical approach**. One needs to be aware of possible misinterpretations for
several reasons. Some spatial correlations might be wrongly interpreted as cause-effect
relationships if vital mechanisms are overlooked, sometimes features are inherited from
eras with completely different conditions. In some cases, extra contextual support can
be derived from good reconstructive studies or studies of actual processes that might
give clues on larger scales.

The above considerations together with experience from the literature led to a choice
of the order of appearance of systems descriptions from disciplinary fields. These reflect
our hypotheses on process-functional hierarchies in general terms. We start with the
larger systems, constraining the smaller ones one way or the other, at least at landscape
scale. We will therefore deal successively with processes in the earth's interior, forces
from the sun and moon, the ocean system, the atmosphere, surface - hydrology and
géomorphology, groundwater-hydrology, soils, vegetation, animal life. This order of
appearance runs roughly parallel with decreasing scales in space and time and
concurrent with an increasing dependence of phenomena on prior systems (Bakker
et al., 1981). This ordering reflects a working hypothesis based on general insights.
Sometimes systems are just slightly more dependent on others than inversely, or they
seem to hang in balance. Moreover, the degree of independence or dependence between
systems can change in time. This is in contrast to situations in which absolutely
dominant systems reign over completely subordinate systems, which are pretty rare.
Hierarchies should thus be considered as being more fuzzy, more complex and less
structured at discrete levels than we would wish.

The concept of hierarchy implies that higher levels set boundary conditions (or
constraints) for the behaviour of lower level units and - inversely - that insight into the
performance of lower level units helps explain the behaviour of higher levels, at least
partly. Referring to the metaphor of 'Janus-faced holons', as put forward by Koestler
(1967) it is crucial to go through the levels, looking upwards to see the higher,
'constraining' levels from the level of interest and looking at the lower levels to gain
insight into the behaviour of the lower units explaining their role for the level of interest.
Going through the levels in this way, looking upwards and downwards from the focal
level, implies that systems are studied from the inside as well as from the outside (see
also Allen & Hoekstra, 1992). Such a treatment inherently means some overlap in
descriptions in this Chapter.

3.2 Sources of energy: from the earth's interior and celestial bodies

Introduction

We have emphasized the role of process-functional hierarchies and, more explicitly, the
importance of energy flows. Thus, we should look first at landscapes and imagine what
is being executed there and where the energy comes from. Winds bring in fresh air
and moisture, raindrops move bare soil downhill or dissolve soil minerals, rivers
assemble water surplus, erode channel beds and transport sediment seaward, tides pump
large amounts of water into and out of sea inlets. Plants build organic tissues and return
a lot of water to the atmosphere, organic material is broken down by armies of
decomposers, earthworms are busy mixing soil layers, herbivores keep vegetation trimmed and predators keep them alert and fit or eat them. Seed dispersal is taken care of by wind, water or animals.

These introductory lines stress that all these mechanisms are at work thanks to vast resources of energy and that we need a short overview of energy sources to understand their subsequent pathways in and between abiotic and biotic (sub)systems.

**Primary sources of energy**

Energy is derived from the following original sources (e.g. Odum, 1983; Summerfield, 1991; Fig. 14):

1) Energy from the earth's interior: heat flow and volcanic or tectonic forces that are manifest on or near the earth's crust, derived from radioactive decay and the cooling of the earth ($36 \times 10^{12}$ W).

2) External gravity forces executed by the sun and moon on a rotating globe: these cause tidal bulges in large volumes of water resulting in tides and tidal currents in the oceans ($2.2 \times 10^{12}$ W) and even solid earth 'tides' ($0.4 \times 10^{12}$ W).
3) Gravity caused by the earth mass itself is a major force, driving flows of matter of all kinds.

4) Solar radiation: this is the overwhelming source of energy ($17.8 \times 10^{16}$ W) running all landscape machineries excluding endogenous geologic processes and tidal processes. As Odum (1983, p. 554) states: ‘The biosphere runs on the flow of sunlight which drives the cycle of the atmosphere, the oceans, much of the geologic systems and the fabric of life and humanity’.

3.3 The geological system

*Time*

I dreamt I lived slowly
more slowly than the oldest stone.
It was dreadful: everything around me
shot up, shook or shivered,
which seemed so silent.
I saw the urge with which the trees
wrenched themselves from the earth
singing fitfully and hoarsely.
While seasons fled,
changing colour like rainbows....
I saw the tremor of the sea,
its swelling and its
hasty shrinking
like a huge throat that would drink.
And days and nights of short duration
flamed and expired, like a flickering fire.

The desperate, eloquent gestures
of things, otherwise unyielding
and their pushing, their breathless cruel struggle.
Why didn’t I realize sooner,
didn’t notice in days gone by?
How could I ever forget again?

*Fig. 15 Time* (poem from Vasalis’ *Parken en Woestijnen*, translated from the Dutch language by the present author and Ann Chadwick)
On a global scale convectional flows in the fluid or plastic mantle material in the earth's interior affect the earth's crust. These driving forces behind major geological patterns are manifest in slow tectonic plate dynamics. Smaller scale phenomena, such as folding, faulting, volcanism or earthquakes are spatially correlated to weakness zones determined by these macropatterns. Many landscape features directly relate to endogenous forces. Sedimentary geology on the other hand relates to the major exogenous processes (ice, water, wind) driven by atmospheric and hydrospheric circulation and gravity.

When seen against the background of relevant landscape-ecological scale domains it can be stated that geological features - exceptionally quick processes or local phenomena excluded - act primarily as static, independent variables that set boundary conditions for an array of dependent variables of water systems, landforms, soils and indirectly vegetation. The scale of geological units is usually large compared with the average scale of landscapes. Landscapes, often delineated on the basis of geomorphological criteria, not infrequently encompass a limited number of geological units. In such cases geology hardly differentiates. This however is no law: some areas, especially in strongly dissected mountainous areas display a large variety of geological formations. The landscape-ecological importance of geological conditions also relates to the mineralogy of hard rock and sediment partly determining soil and vegetation development.

System characteristics

Geology deals with structures in the earth's crust, the materials from which it is built and internal and external forces forming and reshaping the lithosphere in past, present and future times.

A better look at the geological system from a landscape-ecological point of view is necessary. The usual distinction is made between *endogenic* and *exogenic* processes. The first group includes all geological phenomena such as plate tectonics or volcanism ruled by internal forces (Le Pichon et al., 1973; Summerfield, 1991). These crustal plates are driven by convectional circulation cells in fluid or plastic mantle material. Accompanying features of a more regional or local extent and shorter duration follow this global pattern, as is the case with land subsidence or upheaval along the edges of plates, epeirogenic uplift, orogenic-(mountain-forming) processes, folding, faulting, volcanism, earthquakes. Figure 16 shows this geographical preference for some of the features mentioned. This is an illustration of how major (in this case global) mechanisms and patterns predetermine or allow smaller scale phenomena with a shorter duration. One could consider this as an example of a hierarchical ordering within the lithosphere itself: the larger and slower units or processes setting conditions for the smaller and quicker ones.
Heat flow from the earth's interior to its surface is very limited as an energy source. Summerfield (1991; see Fig. 17) estimates this as a small fraction (1/5000) of the amount of energy received from solar radiation. This energy source can be neglected in nearly all ecosystems.

Endogenic processes - if we exclude catastrophic events such as volcanic eruptions or earthquakes - tend to be slow, long-term and usually large-scale. The fastest horizontal
movements amount to 100 mm.a⁻¹, but most movements are slower. Epeirogenic or orogenic uplift or subsidence occurs at rates of about 1 millimetre to a maximum of 10 millimetres annually (Bloom, 1969). The areal extent of the main tectonic plates is somewhere between $10^6$ and $10^7$ km², the time-frame of their activity between hundreds of millions and some billions of years. Large tectonic units have an intermediate position of 1000 km² to some hundreds of thousands of km² and time-frames of millions to hundreds of millions of years (Hugget, 1991). *Changes are generally too slow to be a significant factor in a landscape-ecological context. This is the general rule*, but one should be aware of exceptional or critical situations where threshold values for erosion or deposition are surpassed due to small shifts in erosion levels (gently sloping coasts, river tracks, river outlets) caused by uplift or subsidence.

It may seem that the earth’s crust merely responds to internal forces, but there are notable exceptions. Heavy loads of sediment or large ice caps during glaciation lead to downwarping. During and after deglaciation a rebounce can follow. Such glacio-isostatic processes affected and are still affecting higher and middle latitude areas and mountainous areas. Not only formerly glaciated areas are subject to the rebounce effects, adjacent regions are also involved by exhibiting isostatic reactions leading to subsidence. Process-rates in some areas are relatively fast (up to 1 cm.a⁻¹; Bird, 1985), their importance showing again in areas where a delicate balance is easily disturbed (coastal margins etc.).

*Exogenic processes* imply glacial, fluvial, marine or aeolian processes which modify the earth’s surface by erosion and sedimentation. Changes in topography due to these processes are strongly connected to the realm of geomorphological phenomena. This reflects how difficult it is to establish a divide between the disciplinary fields, geology and geomorphology. In this study we consider the work of exogenic processes primarily from the geomorphological viewpoint and deal with these later (3.6).

*The fact that many geological processes usually act on a very large scale and a long time-scale, and that their direct landscape ecological importance is relatively small is certainly no reason to neglect geology.* The main ecological relevance stems from the physical and chemical properties of solid rock and unconsolidated sediments. These landscape-ecologically independent and rather static variables set important boundary conditions or create possibilities for processes of dependent variables: surface hydrology (permeability of layers), groundwater hydrology (presence and vertical and horizontal extent of aquifers), chemical properties of groundwater (due to solution of minerals), landforms (due to geologically determined differences in susceptibility for material transport, erosional and depositional features), soil development (nature of parent material, especially in initial stages). Related to most other factors is vegetation development. Specific vegetation types confined to soils developed on acid or basic rock are well known.
3.4 The oceanic system

'Big(ger) whirls have little whirls,
That feed on their velocity;
And little whirls have lesser whirls,
And so on to viscosity'

(From Lewis Fry Richardson 1881-1953, cited in Odum, 1983)

The geographical distribution of oceans and large seas mirrors the outcome of large-scale and long-term processes in the earth’s crust which are connected to plate tectonics. Ocean circulation systems, recognizable in ocean currents respond partly to differences in density due to salinity and water temperature, both related to energy balances, water balances, earth rotation (Coriolis effect) and land-sea distribution. Circulation patterns also depend on atmospheric circulation generating currents by wind drag. Gravity from the sun and moon lead to shifting tidal bulges and resulting currents. Tidal ranges are additionally determined by coastal geometry. In many respects there are strong interdependences between the oceanic system and the atmospheric system, due to an intensive exchange of energy and water. It is sometimes hard to tell what is driving what. The expansion and shrinkage of the volume of oceans and seas related to climatic change are well-known features of still poorly understood interactions. These vertical movements result in major changes in and near coastal areas. Climatic patterns, especially wind patterns, determine wave energy distribution in oceans affecting coastal areas as well as storm surge frequencies. Oceanic circulation systems exhibit some sort of self-ordering as found in fluid systems where considerable energy throughput has taken place. There is a ‘nested’ hierarchic ordering, as large oceanic gyres are accompanied by smaller, more quickly turning circulation cells.

System characteristics

Landscape ecology is mainly occupied with studies of terrestrial biotopes. Its briny counterparts, marine ecology and oceanography deal with the remaining 70% of the globe. Nevertheless, the role of oceans and marginal seas on coastal landscapes certainly deserves unwavering attention from landscape ecology. Coastal environments are important enough. Estimates of the total length of coasts amount from 440,000 (Cooke & Doornkamp, 1990) to one million kilometres (Delft Hydraulics, 1991). The relative importance for human settlement and economic activities, as well as a variety of extremely rich ecosystems such as wetlands, exceeds the areal extent many times. Coastal systems are dependent on sea level behaviour (sea level rise or fall), the effect of waves and currents ruling sediment budgets and the main forces driving them.

Oceans represent an enormous reservoir of water (97.6% of the total amount on earth, Nace, 1969), which acts concurrently as storage for energy (warmth) and dissolved components. The exchange of water and energy between oceans and the atmosphere is so intensive that it is often difficult to decide what independent and dependent factors are. Together with the fact that both systems are closely interlocked, their behaviour shows some striking similarities due to common driving forces, in particular the amounts
of incoming energy by solar radiation and the Coriolis 'force' affecting large-scale
current patterns in both media. Oceans respond to differential heating by changes in
water temperature and salinity. Differences in density, together with climatically induced
driving forces on the oceans surface of prevailing winds (e.g. westerlies, trades) lead
to ocean currents (Grant Gross, 1972). These currents, showing both a horizontal and
a vertical direction (upwelling and diving currents), display general patterns akin to
atmospheric circulation patterns (Fig. 18 a en b). Patterns manifest themselves in large,
slowly turning 'wheels', thousands of kilometres wide, accompanied by smaller 'wheels'
with somewhat faster movements. This could be interpreted as an example of self
organization of an open system where energy throughput is the motor behind the origin
and maintenance of patterns. Apart from these similarities between oceans and
atmosphere there are differences. Firstly, the movements in oceans are much slower
since large bodies of water are more inert than air masses. Secondly, mixing of water
is sometimes much less intensive, both in horizontal directions and in vertical directions.
Some parts of the oceans hardly seem to participate in ocean currents (e.g. the
Sargassosea) and it is well known that the layering of water bodies with different
temperature or salinity (thermoclines and haloclines where heavy cool or salt water is
beneath warmer or less salty water) prohibits mixing. The average turnover ratio of
ocean water (exchanging position with the atmosphere) has been estimated at 3000 years,
but some parts have certainly been isolated from circulation for a long period whereas
others have a much more rapid turnover. This contrasts with the situation in the
troposphere where heating from below generates rapid vertical motion.

Fig. 18a Major oceanic circulation
systems (from: Strahler (1969)).
Schematic map of an ocean, major
currents and relative temperature
The picture is emerging of a large, relatively slowly reacting system. Energy and mass flows are governed by solar radiation, earth rotation, gravity and atmospheric influences. One more feature should be mentioned: tidal forces generated by the sun and moon. These, interacting with the coastal geometry, are the cause of a rather differentiated pattern of tidal ranges and frequencies (semi-diurnal, diurnal or other, and spring tides every fortnight) and tidal currents that affect the coastal zone.

Tidal range differs considerably along coasts. A useful division in classes less than 2 metres, 2 - 4 metres and more than 4 meter has been made. Some parts show extreme ranges (over 10 metres; Davies, 1972, Fig. 19). Tidal ranges seem to be decisive for coastal types that can develop, such as beach barriers, barrier islands, estuaries, deltas (Hayes, 1979; Davies, 1972; Fig. 20). An interesting feature is that tidal patterns and processes have specific geographical distributions and limits. For instance, the southern North Sea features two so-called amphidromic cores where tidal ranges are close to zero, whereas tidal bulges rotate around these cores during each cycle.

The impact of seas and oceans on coastal environments is manifest. Slow, episodic and globally working processes are triggered by long-term climatic changes such as the world-wide shrinkage and expansion of the oceans’ volume caused by the melting of land-based ice and the warming of the water-column itself. During glacial periods, water levels are recorded to have been roughly 120 metres lower than they are now which meant that shelf zones usually fell dry, during interglacials (e.g. the Eemien) levels were probably 8 to 20 metres higher (Jelgersma, 1979) and therefore covered lowlying margins. Gently sloping shelves and adjacent land surfaces have registered these changes through erosion and sedimentation mechanisms and related geomorphology. In prehistoric as well as in historic times levels were unstable (e.g. Tooley, 1978 or Pirazzoli, 1985; 1991), partly due to world-wide eustatic processes, and partly to more
regional land subsidence or upheaval along ocean margins. Causes of the latter are tectonic movement or isostatic movements after deglaciation (glacial rebounce) and in adjacent areas subsidence to restore balance. Well-documented behaviour of sea level change reveals rather quick responses to climatic changes in the order of magnitude of a few centuries. (Tooley, 1978; Klijn, 1990b). At present, average rates of 12 cm per century near subsidence areas for the rise of sea level are being observed, higher rates up to 1 m per century are not uncommon (Gornitz, 1991). At such rates, erosion of gently sloping coasts can be considerable. However, erosion also occurs in stable situations with respect to sea level. Bird (1985) estimated that roughly 70% of the world’s sandy coastline is suffering from erosion. It seems that climatically induced changes such as higher frequencies of storms and more severe wave attacks and storm surges can be of prime importance, more so in cases where the sea level is also rising (Klijn, 1990b). These influences sometimes result in rapid loss of land, but they also cause a shrinkage in freshwater lenses beneath sandy or gravelly coastal systems, accompanied by intrusion of salt water and a landwards shift of the sea spray zone (Bakker et al., 1981).

Wave environments, as shown in Fig. 21 reflect the importance of atmospheric patterns (wind direction and wind force which determine wave energy and direction).
3.5 The atmospheric system

In contrast with large scale and relatively slow systems such as the lithosphere or hydrosphere, the atmosphere, despite its huge dimensions shows remarkably fast process rates. Time scales are consequently landscape-ecologically relevant. Since the atmosphere also exhibits an extremely intensive interaction with the hydrosphere, pedosphere and biosphere it is evident that its importance is enormous. Atmospheric phenomena could include many issues and dimensions but for practical reasons we will focus on climatic aspects in the troposphere.

Climate is determined largely by: differential radiation intensities due to the angle of inclination determined by geographical latitude and the position of the earth's axis during the year, to a lesser extent by state variables of the system itself (cloud cover etc.), by the distribution of large land and sea masses influencing energy absorption and release and by [large] mountain ranges (causing deflection of air transport, rainfall on the windward side and rain shadow on the opposite side and a vertical temperature gradient). Moreover, large circulation systems determine vertical and horizontal air flows, emphasizing the effect that energy transport through open systems generates distinct patterns. Forcing functions for this circulation are differential heating of
of the global surface, and from there of the atmosphere, and as a second factor earth rotation causing the Coriolis effect.

Smaller scale atmospheric subsystems, such as frontal systems, seem to occur preferentially along main boundaries between large-scale systems. These atmospheric subsystems and their behaviour are largely independent of landscape features, although major topographic features (mountain ranges) become more important. The very small and rapid atmospheric units, such as thunderstorms are more sensitive to earth surface variables. Mesoclimatic and microclimatic features emerge at this level.

The climatic system is notably subject to both short-term and long-term changes, causing shifts of climatic zones. These changes trigger chains of effects of major importance in dependent variables.

System characteristics

Climate is the average condition of the atmosphere or the 'average weather' (short term phenomena belong to the terrain of meteorologists). Climatic factors are expressed
in a simple set of physical parameters such as precipitation, temperature, pressure, wind, humidity, cloud cover, solar radiation. Averaging weather data, e.g. over a period of 30 years, in order to get the general picture needs to find a balance between a desired simplification on the one hand and the necessary specificity for applications on the other, so that in most cases some measure for climatic variability, e.g. seasonability or the occurrence of extreme events is also included as well.

Climate, climatic zones or regions and climate change are of prime ecological interest, either directly or indirectly. Climate, including incoming radiation, is generally considered to be a major forcing function for all or nearly all phenomena on the earth's surface. At first glance the importance of climate for the character and distribution of soils, vegetational zones, surface water systems, some geomorphological features

![Diagram](image-url)

**Figure 22 Major atmospheric cells in Winter and Spring (after: Lockwood, 1979)**
and even animal distribution can be confirmed by ruffling through world atlases and comparing global climate maps made by Köppen (1931; Fig. 22) with maps of other aspects (e.g. Hugget, 1991). We will elaborate on some of these spatial correlations. Compared with other systems operating on a global scale, the atmosphere can be regarded as a very large, ultra-light system where horizontal and vertical transport of heat and matter is extremely rapid, and turnover rates are high, at least in the troposphere. To get the picture we will go through some elementary issues. Storage-capacity of the atmosphere for energy and matter, such as water, CO$_2$ and O$_2$ is in most cases limited when compared with, e.g. oceans. This emphasizes the fact that atmospheric conditions are, in many respects, strongly dependent on the oceans. Water content in the atmosphere is only one-millionth of the oceans’ reservoir. CO$_2$-content is only one-fiftieth. Atmospheric storage of water is further only a small fraction (about one-thirtieth) of what is circulated annually by evapotranspiration and precipitation, so the residence time is short (Bloom, 1969).

As solar radiation is the original and dominant source of energy, the passing, exchange or reflection in atmospheric layers is of paramount importance. Some of the energy reaching the atmosphere is reflected (20%), some is absorbed by the atmosphere by water vapour, dust and clouds (17%), but an extremely important factor is the earth surface which either reflects solar radiation (10%) or transforms it into heat (53%). The total amount of energy absorbed by the earth’s surface is returned to the atmosphere. This partially occurs by long-wave radiation (6%), but the main portion (about 47%) is transformed into potential energy by evaporation and transpiration, airlifted and made available as warmth and potential kinetic energy by subsequent condensation processes in higher layers of the atmosphere (Forman & Godron, 1986). The global water pump is also a major energy pump! Since water returns as precipitation, a major source of mechanical power is stored in the atmosphere. Bloom (1969) calculated that the land surface (at an average of 823 m above sea level) receives an eroding power that can be compared to a horse-drawn scraper or scoop on every three-acre piece year in, year out. This is the rain-fed and snow-fed part of the ‘geomorphological machine’ (Fig. 23). As global rain or snow distribution is extremely uneven and earth topography differs considerably, this eroding capacity exhibits a highly variable pattern. Simple parameters such as amounts of precipitation, elevation above the sea and the size of catchment areas, are good descriptors of the energy available for major geomorphological agents: rivers and glaciers.

Chemical weathering is also strongly determined by climatic factors such as temperature and net precipitation, influencing the rate of chemical processes, solubility of CO$_2$ in water and percolation rates. This can be seen in soil development rates and soil distribution on earth (3.8).

Order in the climatic system?

Distribution of mean or seasonal temperatures shows predictable patterns on a global scale, mainly determined by latitude (which rules both the angle of inclination of solar radiation and day length), height above sea level (related to a vertical temperature gradient of approximately 1 °C per 100 m) but modified by land-sea distributions, ocean currents and prevailing winds. Large-scale circulation patterns are closely related.
Each hemisphere shows three of these large circulation patterns, represented by convergence and divergence systems known as pressure belts (high and low pressure zones), accompanied by more or less fixed wind patterns (westerlies and trade winds; see Fig. 24). One may wonder why these more or less stable patterns originated. Theoretical explanations could be found in concepts of dissipative structures as described by Prigogine & Stengers (1981) for open systems with a throughput of large amounts of energy. This is but a theory. Simple experiments, however, simulating differential heat transport to rotating basins filled with fluids, generated patterns with remarkable similarities (Richl, 1965). The experiment even showed the origin of wavelike patterns resembling meandering jet streams. The main circulation systems exhibit typical spatio-temporal characteristics in the order of magnitude of 1600 to 10,000 km wide (horizontal distance) and showing annual shifts responding to changes in the sun's inclination and seasonal temperature differences over land and water masses in summer and winter half-years. Smaller scale and faster subsystems can be also discerned, e.g. in the form of cyclones or frontal disturbances frequently occurring in the westerlies where polar air systems meet warmer air (see Fig. 25). The first category generally has dimensions of about 1000 km and a life cycle of about one to five days, the frontal disturbances are even smaller and more ephemeral (see e.g. Hugget, 1991). Even smaller systems (a few hundreds of metres to a few kilometres) with very short lifetimes (hours or even less) are thunder-storms (Dickenson, 1988).
Approximate history of the near-surface temperature of the Northern Hemisphere over the last million years (Quaternary era = Pleistocene + Holocene). $O_h$, $P_j$, $O_j$ are subperiods of the Holocene (postglacial or recent times); they comprise ~1% of the era presented.

*Fig. 27 Climate history (from: Eiden, 1990)*

and witnessed rather sharp changes in annual temperature, winter temperature, summer droughts, frost regimes, gale frequencies and a shift in general circulation patterns, symbolised by a shift in depression lanes of about 3 or 4 degrees latitude. Even within these periods one can recognize shorter periods with distinct warmer and colder temperatures (Bradley & Jones, 1993).

Landscape-ecological effects in previous centuries have not yet been sufficiently studied but they must have been important, as can be deduced in an indirect way from change in land use in agriculturally marginal areas, where failures in crops or fall in productivity or hazards for cattle caused major shifts in land use or even land abandonment (e.g. Parry et al., 1988). Paleo-ecological studies covering the last two thousand years confirm the impact of climatic change on vegetation by a distinct shift in major vegetation zones of approximately 500 km, e.g. by pollen analysis (Gajewski, 1987). It is assumed that natural systems react rapidly to changes in climatic regimes by the disappearance or appearance of species which are sensitive to factors such as the frequency of frost or a change in carrying capacity for herbivores or carnivores which is naturally dependent on primary production. In addition, indirect effects must be regarded as equally important, e.g. changes in river discharge, groundwater levels, flooding regimes. Two important aspects should be mentioned in this context: i) it is crucial to realize that climate change can pass critical or threshold values for biotic, abiotic or human systems and ii) shifts will manifest themselves primarily in the neighbourhood of geographical boundaries or transitions between climate-dependent ecological zones (Gajewski, 1987, Ozenda & Borel, 1990). Effects could show a considerable time lag, depending on intrinsic properties (reaction time) of the systems involved.

The importance of future climate change is deservedly pin-pointed as one of the major
challenges for a variety of disciplines and certainly for landscape ecology which tries to umbrella these (Boer & De Groot, 1990).

3.6 Landforms and their dynamics

Landforms can be considered primarily as rather static backbones of landscapes. Processes modelling the earth's surface are highly dependent on past geological and climatological conditions and their duration, for these are the large-scale variables that determine the resistance of earth layers to erosion, their elevation above erosion bases and the nature and force of agents from the geomorphological tool shed. On the whole, endogenous forces give rise to situations where the earth's crust has been elevated above an erosion base, whereas exogenous forces cause degradation, eventually leading to the levelling of areas.

As geomorphological development in most landscapes is a long-term affair, many landforms have been inherited from past eras. However, short-term, small-scale phenomena can be ecologically very important by returning soil and vegetation development to their initial states. Geomorphic dynamics with relevant spatio-temporal scales, such as encountered in river plains, along coasts or (coastal) dunes are landscape-ecologically of great interest (see also Chapter 2).

It is evident that surface-hydrology and groundwater-hydrology, mesoclimate and microclimate, soil formation and vegetation are highly dependent on relief. This, of course, is not a simple 'one-way-street dependence', for feedback mechanisms are abundant: vegetation acts as protection against erosion, groundwater levels determine deflation etc. Nevertheless, the overall picture seems to confirm that landforms exert an outstanding ordering role for many phenomena.

System characteristics

Geomorphology describes and explains landforms, their origin and age and the processes involved. Strictly reasoning geomorphologists deal solely with the boundary between solid earth and atmosphere and cannot claim an object of study with any material content. In practice, however, surface geology is fully included to explain the origin and dynamics of landforms in combination with endogenous and exogenous processes that act as geomorphological agents. Consequently, it is difficult to draw lines between surface geology and geomorphology (see 3.3).

Geomorphological features can be expressed in static morphometric parameters, such as height above sea-level, height differences, slope (angle, form, exposition), projected base, extent, in dynamic parameters (rate of erosion or deposition), nature of agents (rivers, ice, wind, oceans and seas, gravity, tectonics or volcanism), age and materials in which landforms are developed (see e.g. Leser, 1976; Bull, 1991; Summerfield, 1991). Our foremost interest is what do the driving and other independent factors signify for geomorphological phenomena.
Major agents modelling the earth’s surface

It was explained in 3.2 that forces behind the agents modelling the earth’s surface derive their energy largely from solar radiation through the intermediary agency of the atmosphere, then from gravity and, to a lesser extent from tectonic or volcanic forces. Precipitation in the form of snow and rain in combination with gravity drives the fluvial and glacial agents, atmospheric circulation (wind) runs the aeolian machine as well as wave-induced erosion on the shores, gravity directs water and ice flows and triggers slope transport processes, whereas endogenic forces in certain regions cause specific landforms bound to e.g. faulting or volcanic processes. Rates of geological and geomorphological processes differ considerably, as shown in Fig. 28 (from Summerfield, 1991).

Geomorphological phenomena, when shown on global maps, reflect in many respects the dominant influence of world climate, both present climate and palaeoclimate, together with major geological phenomena. The latter are manifest in orogenetic belts, tectonic features and rock type, which determines resistance to erosion. Exogenic processes in many respects relate to major climatic patterns (temperature, precipitation surplus, wind and wind-driven wave energy (see e.g. Bloom, 1969; Büdel, 1977; 1982; Summerfield, 1991; Hugget, 1991; Davies, 1972: Fig. 29). Apart from the more spectacular processes, most agents take their time to sculpture the earth’s surface,

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<td>Isostatic rebound instantaneous unloading</td>
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<td>Hot spot migration</td>
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<td>Low local relief</td>
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<td>Solution</td>
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<td>Soil creep and solifluction</td>
<td>Mudflow</td>
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Fig. 28 Rates of geological and geomorphological processes (from: Summerfield, 1991)
often many millions years (see Fig. 28). Once formed, these features tend to be rather stable. Only gradually do they respond to changed conditions in subsequent periods. This is evident in extensive regions in the middle and higher latitudes where during glacial periods glacial landforms originated under the influence of ice. In adjacent periglacial areas, fluvioglacial landforms and - where cold and drought prevented a closed vegetation cover - aeolian landforms developed. This morphology is still present and conspicuous in wide zones on earth after considerable changes in climate and the retreat of land ice. This emphasizes the fact that geomorphological landscapes are often legacies from other periods with completely different regimes of land-forming agents. It also emphasizes the fact that correlations between the present climate and geomorphology may seem rather poor, whilst the analysis of longer periods should reveal a far closer relationship between climate and geomorphology.

In this section - in the search for hierarchical phenomena - , as space does not permit us to elaborate on all agents, we have chosen fluvial forms as an example. They affect most terrestrial landscapes, especially under current climatic conditions where the

![Major geomorphological zones on earth](image-url)

*Fig. 29 Major geomorphological zones on earth (from: Hugget, 1991; after Büdel, 1982)*
influence of ice is rather insignificant. Their fundamental geomorphological units are valleys (e.g. Bloom, 1969).

The fluvial system as an example

Any area lying above a regional or global erosion base (lakes, oceans) receiving a certain amount of precipitation is subject to fluvial erosion. The most important driving force for fluvial processes is rainfall transferring potential energy to the fluvial agent. Surface drainage responds to initial gradients in the terrain and as such the initial topography - which has often been inherited from former periods - can be decisive. Rivers transport water, deepen their beds and transport rolling, suspended or soluted material from erosive trajectories to sedimentary regions. The direct incision of valleys is only one part of these mechanisms. Gravity is continuously at work in adjoining slopes where slope processes take care of lateral mass transport to the main conveyor belts (see Bloom, 1969). So the sphere of influence of rivers is many times greater than (former) river bed dimensions would suggest.

Rates of denudation caused by this cooperative action have been estimated on a continental level (North America, average elevation 800 m a.s.l.) to be 60 mm/1000 years. It would take 13 to 14 million years to level the continent to sea level (Bloom, 1969), assuming that rates would not decrease, which is theoretical. Hugget (1991) presents data showing large differences on a subcontinental level related to sediment transport in large rivers. These data reveal very high rates for mountainous areas under tropical conditions (over 1000 tons/km²/year) and very low figures for flat areas in deserts (less than 10 tons/km²/year). In general, hot, humid, mountainous areas show high erosion rates, dry and flat regions low rates (see also Scheidegger, 1990).

The valley may be the fundamental unit of fluvial landscapes, on a higher spatial and organizational level we encounter the drainage basin as an operational unit. Streams are connected to each other in a river system, which forms a coherent network draining a larger morphological unit. Drainage basins have a variable size, between a few square kilometres to a good many thousands, and even larger. The formation of drainage systems in terms of reaching an equilibrium of erosional and depositional processes and the formation of an equilibrium length profile can be estimated between 10,000 and a few million years (Hugget, 1991), although some large river systems are much older (Scheidegger, 1990).

It is far too simple to consider rivers or small rivulets as transport routes for surplus water from surface runoff alone. Even in temperate climates with a relatively even distribution of rainfall, and high frequencies of rainstorms are unable to support a steady flow of streams, since the residence time of water is only days or weeks. If the smaller or larger streams were dependent on surface runoff alone, the stream-beds would frequently run dry. The reasons why they do not can be found in the steady groundwater seepage from valley sides towards the incisions of the streams (Nace, 1969). The steadiness of water flow in rivers is guaranteed by the intermediacy of groundwater, a phenomenon that is often neglected (see 3.7).
Returning to the drainage basin as a fundamental unit it is commonly accepted for ideal or idealized river systems to distinguish three trajectories (e.g. Hamblin, 1975; Fig. 30; Schumm, 1988):

- The 'collecting' part, i.e. the 'proper' catchment where a branched system of tributaries collects water. Stream-bed slopes are relatively steep, erosion predominates, amounts of water markedly increase after each confluence and temporal variability is high. Several approaches to order tributaries according to the number of confluences or junctions passed have been used (see Fig. 31). Generally, this phenomenon is addressed as a hierarchy of stream order (see e.g. Chorley & Kennedy, 1971).
The mid-trajectory, downstream of the collecting area, is the throughput system. Tributaries are less, erosion and sedimentation are more or less balanced, although varying from place to place. The slope of length profiles is less steep, but water transport is more efficient than in upstream areas, as channel forms promote quick discharge without much energy losses due to friction. The main characteristic is a more or less balanced transport of water and sediment. Depending on the nature of water and sediment input channel features can differ. High variability of discharge or high sediment influx easily promote braided channels, a more continuous flow with less material promotes meandering if slope conditions are favourable. Water flow characteristics display a retarded and dampened temporal pattern compared with the quickly and nervously responding rivulets upstream.

The output, or distribution, zone is formed at the river mouth, where entry into still larger river systems, lakes or seas is made. Flow velocity slows down and as a consequence transported material is dropped. This zone is the sedimentation area.
River beds tend to become suffocated by gravel, sand or silt, causing the water to find other channels. The river system forms new branches, and metamorphoses to a distributional system. This results in alluvial fans or deltas.

Drainage patterns in catchment areas are usually shown as dendritic markings, the smaller streams joining each other at junctions to form somewhat larger streams and so on. The question arises as to why nature organizes itself in such a manner and what hierarchical properties we can detect. It is interesting that this branched geometry can be judged on its efficiency in connecting points where surplus water needs to be discharged. According to Allen & Hoekstra (1992) dealing with 'universal' patterns in nature, a branched system connecting all points in a terrain to one main centre (in our case an outlet at the lowest part of an area) has a total track connecting points in the terrain that is exceptionally short compared with other conceivable patterns. Branching therefore is 'a logical choice'. The physical reality of a branched pattern led to the distinction of a hierarchy based on the counting of stream orders beginning at the very upstream parts and their drained surfaces and adding a number at each junction (see Fig. 31). The main thing is that one can distinguish levels in a spatial sense (a spatial hierarchy), but when looking for 'emergent properties' belonging to each next higher level the results are pretty predictable. How systems behaviour as a whole constrains the behaviour of the smaller units in the very upstream trajectories is hardly visible apart from very long-term processes related to headward erosion starting from downstream sections, e.g. after a change in erosion base, affecting all connected tributaries more upstream.

The described fluvial system above can be seen as a rather classic example of a cascading system, which can be split up into three main subsystems (and subdivisions can be made in several minor sub-subsystems), with input - output relationships, downstream retardation and dampening and specific morphological features for each subsystem such as cross-profile, depth/width proportions, water velocity including short-term and small-scale changes in river bed morphology. The concept of a functional hierarchy related to cascading systems based on flow directions and downstream dependences on upstream areas and events, fits very well, but hardly adds to new insights. Most characteristics belonging to stream orders are easily explained by adding and averaging quantities and dynamics in a simple mathematical way.

**Landforms as the backbone of landscapes; the ordering function of the relief**

It is beyond doubt that landforms and land-forming processes are of paramount importance for landscape ecological patterns and processes. Some authors (Finke, 1971; Leser, 1976; Klinka, 1978; Klijn, 1981) stress the fact that geomorphological aspects such as landforms, their height, slopes, curvatures and spatial configuration can be seen as the very backbone of landscapes. This notion stretches further than a static picture determining patterns in other aspects (soils, vegetation), because the geomorphological lay-out also conducts a variety of dependent processes. As such its ordering role is of prime interest.

Looking primarily at the geomorphological configuration as a main-structure of landscapes it is evident how much it directly and indirectly influences other patterns
and processes. Some examples should illustrate this. Macro-relief, let us say from a few hundreds to several thousands of metres causes important gradients in temperature and orogenic precipitation on the windward side of mountain chains and rain shadow on the opposite side. Slope inclination and exposure to sunlight determine amounts and duration of incoming energy per unit of area. Slope characteristics (steepness, length, curves, exposure) determine, together with surface parameters (permeability, plant cover) runoff processes and, depending on the nature of the soil layers or sediments, downslope transport of materials. Where groundwater reservoirs are present in porous layers, flow characteristics and form are strongly influenced by the overlying topography. Relief also influences wind regimes and differences in temperature (e.g. frost 'lakes'), expressing its importance for mesoclimate and microclimate. Some properties are also relevant when terrain-forms are relatively modest. It depends on other characteristics how minor differences in height can be decisive in an ecological sense, for instance when the groundwater level is close to the surface and plant growth and soil development show remarkable differences (Bakker et al., 1981; Ranwell, 1972).

**The effect of geomorphological rejuvenation**

Sub-recent or active processes, local or modest as they may be, have direct impacts on landscape-ecological phenomena. We touch now upon an issue with direct and practical relevance for land and landscape management: natural rejuvenation, either by destruction or by creation of landforms can lead to a complete resetting of soil and vegetation development. Examples can be found in fluvial systems (e.g. meandering), near coasts (coastal retreat or advance), on hillslopes (erosion) or in aeolian or other landscapes subject to wind erosion (Frissel et al., 1986; see also section 4.3; Schumm, 1988; Amoros et al., 1987; Wolfert, 1993; Bakker et al., 1990). Time scales and spatial extent are usually small, rates of change and impact on living systems can however be great (see also 3.9).

**3.7 Groundwater systems**

*Groundwater systems depend on climate as the primary forcing variable (precipitation surplus and its spatial and temporal distribution) determining input. Geomorphology plays a central role in directing water flows. Thickness, areal extent and porosity of rock and sediments determine how much water can be stored. Physical and chemical properties of porous rock and sediments determine flow rates, transport routes as well as chemical properties of groundwater. Geomorphology is very decisive for the existence and spatial distribution of patches where soil and vegetation are directly affected by groundwater. Groundwater can influence characteristics (physical, chemical, dynamics) of soils and soil moisture which in turn are major determinants for vegetation developments and patterns. Groundwater systems can be approached hierarchically by distinguishing large, old and relatively slowly reacting systems carrying younger, smaller and quickly reacting top-systems. These systems can be additionally typified by their chemistry.*
System characteristics

In almost all areas on earth, even in (semi) deserts an incidental or more frequent input of surplus rain-water or melt-water partly infiltrates into the soil and percolates to deeper layers where it builds up and recharges groundwater bodies. Additional sources of groundwater are rivers and lakes acting as infiltration basins. Under-sea or originally marine sediments are usually saturated by saline water and low lying areas can be affected by seepage from adjacent saline or brackish waters. Large amounts of water can be stored depending on the storage capacity formed by fissures or cavities in solid rock or the pores in coarse sediments such as sand or gravel. The total amount of groundwater on earth is estimated as 0.5% of all water on this earth by Nace (1969). This is far less than the amounts of water in seas or oceans (97.6%), but roughly 500 times the amount in the atmosphere and 4000 times the volume flowing in streams and rivers (Nace, 1969).

Residence times of groundwater vary from days or months in top-systems with rapid discharge to surface drainage systems to more than thousands of years. In the Netherlands, an area with predominantly Quaternary and Tertiary and partly Mesozoic deposits, the average residence time is roughly 75 years, in deep and slowly moving systems water older than 5000 years is found (Anon, 1975). Residence time of groundwater systems can be compared with other circulating systems such as the atmosphere (approx. 10 days), rivers (10-20) days and - at the other end of the spectrum - ocean water with 3000 years on average. The relatively long residence time of groundwater and its intensive contact with rock or sediment explains why groundwater bodies have a typical chemistry of dissolved components, reflecting their passage. This is sometimes indicated as its ‘chemical fingerprint’ (Stuyfzand, 1993).

In newly-formed sediments the formation of a groundwater body takes some time - depending on its size and input rates - but after a certain period a temporary equilibrium is settled. The input of water is then balanced by outflow to drainage systems, such as seas, lakes, rivers or small streams, artificial systems, including e.g. artificial groundwater extraction or areas with a net output by high evapotranspiration, e.g. marshes. Discharge to those lower parts of landscapes is then compensated by fluxes from infiltration areas which are mainly found in higher areas where inputs are higher than outputs. Phreatic levels follow overlying topography, in a subdued manner causing differences in elevation and pressure differences. This causes gradients in groundwater potentials water flows. Water-flows respond to vertical and lateral vectors resulting in curved flow-lines along which the movement of water particles takes place. This is the picture for homogeneous and isotropic media, but situations are usually more complex due to the existence of hydrogeologically determined differences in permeability for vertical or horizontal flow. Impermeable or semi permeable layers confine more permeable layers, the so-called aquifers. Rates of water flow and the amounts of transported water per time unit depend on pressure differences per unit of distance (gradients) and layer characteristics such as thickness, porosity and permeability. Flow rates vary from 1 m.day\(^{-1}\) to 1m.year\(^{-1}\) (Anonymous, 1975). Simplifying the whole matter: driving forces for groundwater flow are precipitation minus evapotranspiration (land cover as decision variable!) over the area, the pull of gravity determined by topography in combination with surface drainage or other output factors. Boundary
conditions for flow rate and flow direction strongly depend on the geological structures and facies. Processes are driven by the local, regional and even global hydrological cycle which originally derives its energy from the sun.

Some new visions on groundwater systems

So far a general description of groundwater systems, from which a picture of independent, forcing or constraining factors, thus a process-functional hierarchy, is emerging. The question is whether we could detect other aspects of hierarchies, e.g. in space or time. Before going into this a short excursion is inevitable.

The classical approach of groundwater hydrology was to distinguish between aquifers and semi-permeable or impermeable layers and execute many calculations of input and output factors, mainly focused on applications in drinking water supply or use in agriculture. The latter applications form the realm of agrohydrology engaged with aspects of the unsaturated zone, the phreatic water and the surface drainage systems.

Both categories of applications were primarily interested in quantitative aspects, although a basic water quality was of course necessary. Environmental problems gradually summoned more attention for water quality aspects. In ecology (or landscape ecology) analogies with agrohydrology are evident and need no further explanation. In addition however, ecological studies revealed the importance of sometimes small differences in water quality. The quality of soil water and, equally important, surface water can be characterized by its nutrient or mineral composition (e.g. calcium content) and related variables such as pH and buffer capacity. These variables are indisputably vital for ecosystems (e.g. Grootjans et al., 1993). As a consequence more attention was given to studies of the pathways of water through deeper layers. This intense interest in water quality, existing in aquatic ecology for a much longer period, is being more and more acknowledged in terrestrial ecology and has given the impulse for a new discipline: ecohydrology (Van Wirdum, 1981, 1991, Kemmers, 1985, Pedrolì, 1987, 1992).

These developments coincided with a conceptual change within hydrology itself since the sixties. Largely after Tóth (1963), Engelen (1992), Jones (1986) and Van der Heijde (1988) we will now mention some important shifts such as:
- the importance of water chemistry, to explain either the influence of natural processes or polluting sources, such as nitrates or toxic components.
- the concept of water systems which are seen as being more or less coherent water bodies with a distinct origin or source area, age, water chemistry, flow dynamics and response time, which can be spatially separated from other systems. Such water systems are not necessarily congruent with (the concept of) aquifers: system boundaries cut through aquifers!
- more attention for the main driving forces or other decision variables working on the surface (climate, topography, vegetation)
- the perception of size and spatial position of groundwater systems such as the distinction between relatively small, superficial, quickly responding systems with a short residence time and larger, deeper, slowly moving water bodies with a longer residence time.
- the notion of a strong interdependence of groundwater systems and surface water
- the awareness that water systems sometimes have a long development time or relaxation time after changes (e.g. shrinkage, extension). Relaxation time could be hundreds or even thousands of years (e.g. Bakker, 1981).

- the awareness that other parameters should be advocated to describe and understand groundwater systems (e.g. natural tracers but also parameters on the input or output side, such as topography or plants indicating upward seepage).

These changes in approximation were put forward by Tóth (1963) and elaborated upon and refined by Engelen and co-workers (e.g. Stuyfzand, 1993). Stuyfzand developed a method of classifying water types based on their chemistry, as determined by origin, age and flow. A range of studies was published whereby the concept of groundwater systems secured a firm base. They demonstrated the existence of several water systems, differing in size and relative position. This phenomenon has been described as hierarchically ordered, so-called nested systems (see Fig. 32). We draw attention to the fact that this spatial configuration of systems directly refers to spatial nesting, as explained in 2.5. Systems and subsystems are delineated by their size and superposition. The smaller and younger systems ‘float’ on the larger and older systems. Smaller systems generally have shorter cycles and react more quickly to changes in input, e.g. changes in water quality. They respond to changes in larger systems and at the same time affect these systems by exerting pressure. As such this reflects hierarchical characteristics already explained, stating that smaller systems are constrained by larger systems, but - inversely - also influence the behaviour of larger systems. One could classify systems according to their size and lifetime (see Figs. 33 and 34) as well as to their complexity.

**Groundwater effects on soils and vegetation**

Groundwater systems, determined by atmospheric input, topography and geology set conditions for dependent systems.

Groundwater, by its quantitative and qualitative features, embodies a set of relatively independent and decisive factors for soil and vegetation development. Important soil-forming processes which we will deal with in the next section, are the leaching of minerals, organic substances and clay, the input of organic material and its decomposition. Both the nature and rate of these major soil-forming processes are strongly influenced by the occurrence of shallow water tables and the chemical composition of soil moisture. The most prominent effect depends on flow direction: infiltration leads to leaching, exfiltration to enrichment of the root zone with basic ions. Shallow water tables imply water-logged soils. This i) not only hampers leaching but ii) leads to a marked decrease in the decomposition of organic matter and iii) results in stronger denitrification than under dry conditions. Moreover, upward seepage of groundwater enriched during its passage through mineral-rich layers with calcium, iron and other bases compensates for leaching processes in top soils or even leads to gradual enrichment. Groundwater affecting the root zone also influences plant cover directly, as species need to be able to adapt to waterlogged situations. Vegetation responds to all these physico-chemical factors and obviously reacts critically to any change in those conditions (Kemmers, 1985, Kemmers & Van Wirdum, 1988; Grootjans et al., 1992).
Fig. 32 Groundwater systems. Smaller systems 'floating' on larger systems (after Tóth, 1963)

Fig. 33 Groundwater systems and surface water systems hierarchically ordered (from: Stuyfzand, 1993)
3.8 Soils

Soils, soil patterns and soil dynamics reflect the influence of climate, parent material, relief, groundwater, vegetation and time. Climate is often a dominant large-scale factor, the influence of parent material decreases during time whereas the importance of vegetation increases. Groundwater influences are distinct, whereas spatial characteristics are strongly determined by topography: they often seem to act as co-varying factors. Soil development in its ecological setting points to the crucial importance of soil chemistry. One can recognize chemical hierarchies playing a role in the buffering mechanisms that cause cations to leach in a certain order. In more mature soil-plant systems, the interaction of soils and vegetation is so close that interdependence is more emergent than dependence. Soil characteristics however are very determining for plant growth in initial stages. Nature and rate of soil development processes are in many respects determined by the soil water status. Soils being dependent on such a variety of landscape factors can be consequently interpreted as compound indicators of these circumstances. Some soil characteristics reflect long-term developments, others such as organic horizons, react more rapidly to environmental or vegetation changes.

Systems characteristics

Compared with the lithosphere, the hydrosphere or the atmosphere, which are kilometres or tens of kilometres thick, the pedosphere has an extremely thin veneer. (Definitions about relevant thickness differ: some take the average ploughing depth or average root
depth, some use the depth of soil augers used for soil mapping, and some assume two metres to ensure that capillary rise is being considered. From a pedogenetic viewpoint, the depth of soils is defined by the extent of soil-forming processes which lead to distinct soil horizons, such as leaching, illuviation of clay or other components.

Soils are three-phase systems (gases, fluids, solids) within which the influences of the atmosphere, hydrosphere, lithosphere and biosphere are interwoven and where physical, chemical and biological processes are synchronously and interdependently at work. We could state that the soil system is a very thin, complex and busy compartment. It can really be regarded as ‘a reactor’ (Richter, 1987) when one realizes the intensity of flows and transformations of energy and matter that take place.

Although trivial, we stress the fact that soils, compared with the atmosphere and hydrosphere, are subject to processes that are usually vertical in nature. Infiltration of rainwater, evapotranspiration from the soil surface or via roots, exchange of gases, input of organic compounds, absorption and release of heat, weathering, solution, transport of solutes are nearly all vertically oriented. This explains the genesis of distinct horizons with enrichment in organic material, eluviation of minerals and clay from top layers and illuviation in lower layers. This is the case in humid areas. In (semi)arid areas, upward transport of salts can lead to enrichment of top layers. Of course this predominance of vertically oriented transport is the rule in most flat lying terrain and in well-stabilized slopes. Elsewhere, slope processes take care of the downslope transport of topsoils and sometimes even deeper layers. Lateral flow of soil water occurs in interflow processes.

Soil forming factors

For soil-forming processes and current behaviour of soils, the answer to the question of which factors play the main roles and how they can be judged upon their relative independence or dependence is essential. In a classical study, Jenny (1946) stated that five, independent, soil-forming factors are at work: parent material, relief, climate, time and a biological factor (availability of) plants, animals (soil fauna) and also man. Should one really be confronted with independently varying factors which could be each split into numerous variables the resulting complexity would leave us with an unmanageable set of possibilities. This somewhat discouraging picture, however, is not consistent with numerous observations, among which the later studies of Jenny (1958, 1980), which i) point to the fact that some factors dominate other, more dependent factors, and ii) indicate that some ‘independent’ factors are strongly connected in field situations this could be addressed as the ‘correlative complex’ (Zuur, as referred to Steur, 1990) as we will illustrate with respect to relief and groundwater (and vegetation) and iii) indicate that time as a soil-forming factor actually needs separate treatment. Without trying to cover all relevant literature (see e.g. Vos & Stortelder, 1992) it is noteworthy that climate (again!) is indicated as a dominant factor determining both soil and vegetation development. The importance of parent material as a dominant factor in initial stages of soil and vegetation development is undisputed, but its importance gradually decreases due to soil changes. It can easily be understood that time as a soil forming factor (read a long-term effect of e.g. eluviation, influx and decomposition of organic matter) tends, little by little, to overshadow the influence of parent material especially in draining soils.
Another nuance can be recognized when realizing the usually strong coupling between topography (relief or geomorphology) and the directly related influence of groundwater systems close to the surface. At least locally or regionally this is a very decisive factor for soil formation and behaviour. So the initially discouraging picture of five independently varying factors can be replaced by a more simple and operational concept in which climate, parent material and topography (with groundwater as co-variable) are the independent factors, soil and vegetation dependent factors. Their mutual dependence on parent material and to a lesser degree on climate decreases in time, e.g. by an efficient circulation of minerals between plant cover and organic soils substances or due to the fact that some vegetations in waterlogged sites make their own soil from dead organic matter (peat). Vos & Storteld (1992) summarize these shifts under the heading ‘From causation to correlation’. This still leaves the problem of how to understand the relationships between soil and vegetation unsolved: is there any functional hierarchy between these two subsystems or not? Many the phenomena indicate intricate relationships. Sometimes the soil system emerges as being dependent on vegetation, the latter offering soil cover, causing enrichment with organic compounds. But and with even more conviction the is more often true. Soils are the ‘sine qua non’ condition for any plant growth for germination, foothold for roots, supply of water and minerals, shelter during hibernation and so on. In most cases the relative dependence of vegetations from the edaphic factor is evident, e.g. in cases where initial plant growth starts or where disturbances in vegetation are followed by processes that again are primarily governed by soil characteristics. So, complete correlation of soil and vegetation is a special case due to long-term co-evolution of both complexes in an undisturbed situation whilst a fall-back in abiotically determined stages is easily accomplished and re-emphasizes an asymmetric relationship.

**Soil patterns as a clue for dependences**

The above picture of soil formation is consistent with patterns that can be derived from maps showing climatic, geological, geomorphological and other phenomena on the scale of continents. Climate is evidently a major decisive factor of weathering, leaching, plant productivity and consequently soil formation, although some features could mirror fossil rather than actual conditions. Zonal soils had already been recognized in the last century both in the USA and Russia (Hugget, 1991). Climatic gradients in these regions are distinct and well expressed without interference of other factors. Many studies have confirmed the role of climate (see e.g. Hugget, 1991; Sevink, 1991). It is interesting that climatic parameters such as actual evapotranspiration and mean annual temperature and the so-called ‘leaching effectiveness’, computed from climatic data can be translated into classes that set distinct (!) limits for major soil groups (Hugget, 1991; Fig. 35). Climate as the main controlling factor for the development of peat soils was studied by Lottes & Zieglar (1994) who demonstrated a very close relationship between global distribution of peat soils and simple parameters such as precipitation and temperature and their seasonality. Climatic influences, more precisely those variables conditioning soil processes and their rates such as temperature and precipitation, logically determine development time of soils. Fresco & Kroonenberg (1992) point to differences in leaching in humid tropics compared with temperate regions. Rates depend on parent material, climatic factors and plant cover. Some more specific soil characteristics, such as soil nitrogen contents, mirror climatic gradients (Hugget, 1991).
Fig. 35 Soil groups positioned after major climatic variables: evapotranspiration (y-axis) in three temperature regimes (from: Hugget, 1991 after Arkley, 1967)

Within the large-scale zonation of soils (or climo-sequences) - as if they were painted with a very wide brush - other patterns, such as parent material and macro-relief, also set their stamp. At a more detailed level other aspects emerge, such as small differences in elevation, soil moisture as related to groundwater and vegetation composition insofar not already reflecting large-scale climate zones. These patterns are painted with a much finer artist’s paint brush. This picture can be found in detailed soil maps or cross-sections (e.g. Fig. 36) and is an expression of the catena-concept (literally ‘chain’ of soils) that tries indicate how soils are arranged in an orderly and repeated pattern in landscapes as a result of their relationships (dependence on) topography (the so-called topo-sequence) and age of soils (the so-called chrono-sequence).

Soil chemistry and its ecological importance

When soils are considered from an ecological point of view, and especially for (semi) natural vegetation, soil moisture statuses and soil chemistry are of prime interest. We will focus on soil chemistry and take leaching and soil acidification as an example.
It is well known (see e.g. Ulrich, 1981) that the soil solution, i.e. its specific balance of cations and anions, is an expression of chemical ‘equilibria’ between the liquid phase and the solid phase. ‘Equilibria’ is put in inverted commas because many processes are at work to unbalance the situation: percolation of rain-water including dissolved components (e.g. CO$_2$, other man-induced acidifying components, input in the soil of CO$_2$ by soil respiration, input of organic matter and subsequent decomposition and mineralization products (e.g. humic acids and NO$_3$, resp.), weathering of minerals, hydrolysis, adsorption and exchange to and from adsorption-complexes (clay, humic compounds), plant uptake and losses by leaching (e.g. calcium, magnesium, iron). See for further explanation De Vries, 1994).

Input of acidifying components and output of basic components by leaching is strongly determined by the nature, rate and duration (kinetics) of chemical reactions and their interactions. Acidifying and leaching processes set in motion several buffer mechanisms with distinct pH-trajectories and kinetics. The surplus of H$^+$ influx primarily leads to the dissolution of calcium-carbonate in the pH trajectory above 6.5 (carbonate buffer range). When carbonate is depleted and the pH trajectory is between 6.5 and 4.5 silicate weathering and cation exchange from the adsorption complex take over (silicate
buffer range), whereas below pH 4.5 dissolution of aluminium hydroxides is the dominant buffer (Ulrich, 1981; De Vries et al., 1989; Fig. 37). These mechanisms in soil chemistry illustrate the principle of a chemical hierarchy (Odum, 1983). This insight can be elaborated further by including rates of weathering or exchange, in order to determine whether these mechanisms are able to counter depletion processes adequately. We intentionally took an example related to the soil reaction (pH status) for ecologically important variables. As emphasized in several handbooks (e.g. Bannister, 1976) pH is a very determining factor for the solubility annex availability of cations for plants (Fig. 38) and the rate and nature of mineralization processes, such as nitrification and ammonification. Decomposition of organic material is strongly inhibited in low pH trajectories, which also affects nutrient cycling. All this emphasizes the importance of pH and the eminent relevance of chemical buffer processes.

![Fig. 37 Chemical 'hierarchies' represented by various mechanisms causing pH buffering in soils (from: Brink et al. after data of De Vries)](image)

Variation in soil properties and availability of ions in relation to pH (after Schroeder 1969 and Larcher 1973a). The breadth of the band is related to the degree of activity of availability (i.e. broad bands indicate high availability).

![Fig. 38 The role of pH determining the availability of plant nutrients (from: Bannister, 1976)](image)
This emphasizes the importance of the mineralogy of parent material (parent material > soil weathering > pH > nutrients > plant response). Using the same example in a somewhat other direction the importance of soil moisture conditions should be stressed. Assume a groundwater system (acting as an independent variable) which causes both permanently saturated soils and an influx of basic ions by upward seepage. Input and throughput of rain surplus decreases, denitrification increases sharply, so that acidification diminishes, plant growth is less vigorous in permanent wet conditions and decomposition and mineralization processes are significantly reduced in these anaerobic environments. All these partial effects cooperate to reduce soil acidification. Net input of basic ions from upward seepage represents an extra buffer protecting the solid phase from loss of cations. It follows that groundwater, if present in the very top layers of the soil system, by its presence alone and sometimes by its chemical composition is a very dominant landscape ecological factor for the dependent factors, i.e. soil and vegetation. Small differences in ionic composition are already leading to significant differences in plant composition (ref. Grootjans et al., 1993; Kemmers, 1986; Bakker et al., 1981).

3.9 On plants and animals; in search of operational levels for landscape research

Plants and animals are goal variables for food or other resources and for biodiversity. Their role in uptake, storage and release of energy and matter is crucial on each scale, varying from small plots to the entire biosphere. Landscapes harbour plant and animal species in astonishing numbers. Their numerous and complex relationships are proverbial. To reduce this variety and complexity to manageable proportions requires a mode of intelligent lumping. For plant species such a (functional) clustering should link abiotic variables which differentiate at landscape level: temperature (distribution), light, macro- (and sometimes micro-) nutrients, water availability and their dynamics. Animals depend on vegetation through its primary production, its vertical structure and its role in landscape heterogeneity (horizontal structure). Their position in food webs (herbivores, carnivores, reducents) is important. Functional groups of animals should at least encompass these factors.

Several phenomena in ecology point to hierarchic ordering: 1) the importance of abiotic boundary conditions showing in the response of plant and animal distribution to climate, hydrology and soils ii) the existence of trophic levels as determined by energy flow iii) ecosystem characteristics in which population dynamics are constrained and stabilized by several mechanisms (e.g. prey-predator relationships), iv) biogeographical phenomena (metapopulations) and v) social ordering. Each of these hierarchically ordered phenomena responds to its own mechanisms, that seem to operate rather independently and synchronously in landscapes. If living nature is hierarchically ordered, it does not respond to one ‘grand design’, but to several different domains of hierarchic mechanisms that deserve separate treatment.
Introduction

The lay-out of this section is somewhat different from the preceding ones. Biological systems, - plants, animals, ecosystems in their overwhelming variety and complexity - can only be approached in a concise framework by using some central concepts from plant and animal ecology without bothering about details or nuances.

Species at the beginning and at the end of the road; the need of data reduction.

As far as landscape ecology is concerned plants and animals are at the beginning as well as at the end of the road. From the viewpoint of biodiversity, plant and animal species deserving conservation or rehabilitation are goal variables. The end of the road refers to the fact that plants and animals are dependent on the boundary conditions set by other abiotic systems, which we have covered in preceding sections. Their dependence make plants and animals extremely sensitive indicators of abiotic and biotic circumstances though it is often extremely difficult to unravel what exactly is indicated by their presence or absence. To clarify the position at the dependent end of the process-functional chain some basics from ecology are worth mentioning.

Plants are autotrophic organisms that within certain limits of temperature (-60 to + 80 centigrade, e.g. Vogel & Angermann, 1967; Hugget, 1991) directly exploit solar radiation, water, macronutrients and micronutrients, carbon dioxide, oxygen, and a bit of space. As the last three factors do not really discriminate in (landscape) ecological studies (though oxygen and carbon dioxide can control aquatic systems) most explanatory power for the distribution and dynamics of plants can be derived from the other master factors (temperature, light, water, nutrients) which show large variations. Conceptually, these environmental factors and related sets of variables could be put along axes, with the range from very low to very high. The outcome is an imaginary multidimensional space representing the plant environment and its limits. Within this abstracted envelope of possibilities each plant species has its own sub-space with specific trajectories from the minimally required to the maximally tolerated conditions: the so-called ecological amplitude. One could add a few factors to those listed above, for instance resistance to mechanical influences or grazing. What then emerges is the specific functional profile, or 'niche' (Hutchinson, 1958; Pianka, 1976). Without interference from other species this is the so-called fundamental niche. In field conditions, this niche is seldom fully exploited as other species also demand their place and resources (competition); what results after taking interspecific competition into account is the so-called realized niche. Returning to the metaphor of a multidimensional space it is clear that those plant species living near the extremes of the axes, where one could speak of (almost) too little or too much, should be adapted to harsh or limiting conditions, e.g. drought, extreme cold or shortage of essential nutrients. These inhospitable conditions for plant life are addressed as stress. One could extend this rather static view to the adaptation of plants to all kinds of disturbances or catastrophes, such as fire, flooding, etc. These hazards require other adaptations than the more regular or continuous environmental stress to guarantee survival of the species. For instance, effective reproduction techniques are an answer to overcoming lethal conditions during harsh periods by investing in a new generation.
Just like plant species animals are also able to adaptation so that they can exploit and withstand their environment effectively. The niche concept is thus equally appropriate animals. There are, however, differences.

According to Boulding (see 2.3) the animal kingdom distinguishes itself from plant life by increased mobility, teleological (goal-seeking) behaviour and self-awareness. Animals are equipped with information-processing sense organs, helping them to observe their surroundings and react adequately to information on e.g. food availability or danger. This explains their well-developed nervous systems. Moreover, there is the ability to learn, additionally, the existence of social organization and effective ways to communicate, at least within the more highly developed forms of animal life. Animals are heterotrophic organisms feeding on sources of energy that are directly or indirectly supplied by plants. Energy can be released by metabolism, a process that demands oxygen (respiration) to maintain body functions and allow the animal to perform actions requiring energy. Animals can be subdivided according to several criteria, such as their position in energy flows (herbivores, carnivores, decomposers), size, sessile versus mobile, biotope (e.g. water, land biotopes), migratory or non-migratory, way of locomotion, life-span, reproduction techniques, social structure, range of action and some other criteria. Animals display a conspicuous dependence on plants for their food - especially the herbivores - and in addition on vegetation structure (vertical and horizontal structures in plant cover; e.g. Krebs, 1985). Animal species have sometimes evolved to become pure specialists, strictly bounded to (micro) habitats in for instance vegetation structures. Horizontal landscape heterogeneity is equally important. Different parts of heterogeneous landscapes are exploited for various animals actions, such as foraging, drinking, resting, nesting, sheltering and so on. Biotope differentiation and the multiple use of various biotopes emphasizes the importance of vegetation structure and patches in landscapes. Of course, as animal species differ largely in mobility, the horizontal scale (extent of biotopes, distance) of landscape features is extremely important.

Towards a functional grouping of species?

The species level, though fundamental in biology and its applications, is sometimes hard to handle. There are generally many species in an average sized area and the use of the species as a working unit brings about practical problems. Apart from this, a listing of species, e.g. in the flora of an area, is still rather abstract and far from practical. It lacks information on geographical extent, numbers, position, interrelationships between species and relationships with abiotic features. If all this information were to be attached to the list of species one would be confronted with an unmanageable pile of data. To quote Allen & Hoekstra (1992), in their treatise on research levels in ecology: 'More than in any other subdiscipline of ecology, landscape ecologists are buried in data. A casual glance across a vista reveals an unmanageable mass of detail'. This conclusion is especially pertinent to biological data.

Landscape studies have to cope with tantalizing numbers of species. On a global scale Wilson (1988) comes to a number of roughly 1.4 million described species. The numbers in an average study area are far less, but not too modest either. Depending
on climatic zone, abiotic heterogeneity and various other factors (see e.g. Clapham, 1973; Krebs, 1985) in an area of average size, the number of vascular plant species can amount to many hundreds or thousands, numbers of vertebrates to many hundreds and if one were to add all invertebrates (including soil fauna) one could easily end up with many thousands of species, as is the case for a small country like the Netherlands (Wolff, 1989). To identify, quantify and localize all organisms is a frightful job. Even then it is only a small part of the job, because relationships between organisms are equally important. There are very many of them and they are still poorly understood. And, when really aiming at the ecosystem or landscape level all relevant links to abiotic patterns and processes should be included. Despite all the knowledge gathered so far - even the idea to approach landscapes and their living contents starting from species level and keep juggling with all species during the study would be foolish. This is not the same as saying that we could do without knowledge at this level! Autecological knowledge is necessary as the hard core for generalizations on higher levels. What we are trying to emphasize here is the inevitability of intelligent lumping: clustering, aggregation, regionalization.

Starting from the position that abiotic conditions are decisive for many botanical phenomena, either directly or indirectly, the most beneficial way of accomplishing data reduction in plant species would be to lump them according to their functional relationships with the abiotic environment. For animal species the starting point would be somewhat different, as these respond primarily to vegetation composition and structure. Starting points that could be regarded as useful or promising are dealt with below. We will do this in a certain order: firstly we will try to identify general notions at species level that may allow lumping. This will be illustrated by some examples from botany and, to a lesser degree, from zoology.

Starting with the species as a unit, several attempts have been made to classify plant species on the basis of morphological properties that are considered to be a functional adaptation to environmental factors, e.g. drought or cold. One of the first and still convincing efforts was made by Raunkiaer (1934) who grouped plants on the basis of their physiognomy. The outcome proved to offer possibilities for correlative studies including climatic and edaphic parameters. Another approach put forward by McArthur & Wilson (1967) made a distinction in so-called strategies - useful for both plants and animals - indicating species as stress-tolerant, e.g. by their build and other physiological adaptations enabling them to withstand drought or cold, the K-strategy and the r-strategy indicating species effectiveness in reproduction techniques when environmental conditions are too difficult in one way or another. A very vivid type-casting of reproductive strategies is described by Urban et al., (1987): ‘A fugitive on a larger scale .... that wins the war, though it loses every battle’ (competition!). A related, even more appealing concept constructed partly on these earlier ideas was put forward by Grime (1979) and Grime et al. (1988). Grime distinguishes several (plant) strategies towards stress and disturbance, by introducing the C-S-R model. C represents competitors, species which are effective in environments that are low in both stress and disturbance, ruderals (R) that are successful in environments with disturbances of all kinds, often by quick, reproduction and effective dispersal (comparable to r-strategists), and stress-tolerators (S) (Fig. 39), a term used for species morphologically and physiologically equipped to adapt to withstand extreme drought, frost or low levels in nutrients.
Fig. 39 Classification of plant species according to their strategies towards environmental factors (from: Grime, 1979)

A model describing the various equilibria between competition, stress and disturbance in vegetation and the location of primary and secondary strategies. C, competitor; S, stress-tolerator; R, ruderal; C—R, competitive—ruderal; S—R, stress-tolerant ruderal; C—S, stress—tolerant competitor; C—S—R, 'C—S—R strategist'. $I_c$, relative importance of competition (—); $I_s$, relative importance of stress (— —); $I_d$, relative importance of disturbance (—). The strategic range of four life forms is also shown: (a) herbs, (b) trees and shrubs, (c) bryophytes and (d) lichens.

A complementary and extremely useful approach is to attribute plants, more or less loose from their strategies, to their abiotic position. Plants can be categorized into pH trajectories, along an axis from dry to wet, and from low to high nutrient availability. This was done by e.g. Ellenberg (1974), Runhaar et al. (1987) and also by Grime et al. (1988). Some of these classifications include development stage or substrate dynamics. Ecological groups of plants can be formed in such a way.

Spatial correlations as a clue?

The world distribution of plant species, when classified after life-forms as explained above confirms the utmost importance of primary factors such as temperature, water
availability, nutrients and light including seasonal extremes. This can be illustrated by maps of the zonal distribution of major life-forms compared to independent climatic factors such as temperature, net radiation, water balance (e.g. Hugget, 1991). It is interesting that plant distribution, when correlated to such climatic factors, reveals the existence of certain threshold values in temperature or water balance that mark the geographical and temporal transitions from major vegetation types such as tundra, conifers, deciduous broadleaf, evergreen broadleaf etc. (Woodmansee & Williams, 1987; Fig. 40 a and b). On a more detailed (species) level it is well known that plant species

Map of the Vegetation of the World from Polunin (1960). Symbols as for Fig. 2 and (•), grassland/scrub/desert.

Predictions of global vegetation on the basis of temperature, precipitation and the annual water balance (precipitation - evaporation).

Fig. 40 World distribution of vegetation zones (a) and its prediction using climatic variables (b) (from: Woodward & Williams, 1987)
distribution is strongly determined by specific climatic factors acting as stress, such as frost frequency or summer drought. Support for the awareness of climate as an important variable can also be found in the relative frequency of certain strategists in climatic zones. Many reproductive strategists are found in tundras, whereas other strategies prevail in less harsh conditions (e.g. Clapham, 1973).

Relationships between plants, climatic factors and edaphic factors such as nutrient availability and soil pH (also affecting nutrient availability) are manifest in many respects. Together with a favourable temperature regime and the availability of water nutrients determine vegetation productivity, a sum-parameter with a twofold ecological relevance. Productivity proves to be a variable that strongly correlates to species diversity (Al-Mufti et al., 1977; Grime, 1977). Both very low productivity and high productivity are relatively low in plant species, probably because these trajectories in nutrient availability are dominated by a few well-adapted plant species that are either stress tolerant or good competitors (for light). Secondly, productivity of plant cover can be interpreted as the basic energy supply for dependent organisms, such as herbivorous and - indirectly - carnivorous animals. The greater the supply, the greater the carrying capacity for dependent organisms. This will be dealt with later in this section. Soil pH as a determinant for plant species composition and number of species is well documented, e.g. by Grime (1979). Figure 41, from the latter author gives a comprehensive picture for the British Isles of species richness related to both plant productivity and soil pH.

These examples dealing with the relationships between plants and plant related variables on the one hand and climate or soil parameters on the other, stress the strong dominance of abiotic factors. This dominance is manifest and undisputable and can be seen very well at biome scale. However, it has been noticed that in certain well-developed and highly structured vegetation types, such as mature forest ecosystems, soil conditions and microclimate gradually become more influenced by the plant canopy itself. Such vegetations seem to have detached themselves from abiotic constraints to a certain degree: they form their own soil, their own microclimate, and by developing a more closed cycle of nutrients the system tends to become relatively independent. This relative (!) independence however originates within the limits set by the environment!

![Fig. 41 Plant species number related to standing crop and soil pH (from: Grime, 1979 after data from Al-Mufti et al., 1977)](image)
The ecosystem level, with special attention to energy flows

One of the central pillars in ecological theory directly relates to the flow of energy through the various components of the ecosystem (Tansley, 1935; Lindemann, 1942; Odum, 1971; 1983). Energy flow starts with an autotrophic organism converting solar radiation by photosynthesis into chemical energy (organic compounds). By analysing the pathways and fate of these primary sources of energy in subsequent "layers" in trophic levels, our understanding of basic rules or laws in ecology has been extended enormously. Energy from plants is used for metabolism by the plants themselves and is used by herbivorous animals. Carnivores exploit the energy stored in their prey and sometimes they themselves serve as food for top predators. This flow of energy - and concomitantly of necessary minerals - is an excellent example of a cascading system, in which the output of an "upstream" system forms the input of the next system. It has been established that due to the use and losses of energy within each system (trophic level) and at the transfer, an average "loss" of roughly 90% occurs (May, 1976; see also: Figs. 42 and 43). Trophic levels, expressed in so-called food pyramids, are therefore limited in number. A number of four levels is rather common, six levels exceptional. It is evident that more building blocks on the food pyramid would prove impossible, as these imaginary "top-top-(top)-predators" would meet the limits of their energy resources. This energy-loss is a real constraint as these "super-predators", needing body sizes and operational performances exceeding those of their prey, would require larger and larger areas to get enough prey. Covering such large areas however demands considerable energy and time, which logically limits the number of trophic levels.

Flow of energy in a natural community. In a steady-state community the intake of photosynthetic energy on the left, and the dissipation of energy back to environment toward the right, are in balance; and the pool of energy of organic compounds within the community remains constant.

Fig. 42 The flow of energy through ecosystems (from: Whittaker, 1970)
Energy flows in ecosystems (Odum, 1975). Solar-energy flow in kcal/m² per year, as shown in a pictorial diagram (A) and in a more formalized flow diagram (B). The heat sink symbol (↓) in (B) shows where energy is lost in transformation. Five losses where useful work is done are as follows: (i) Attenuation of extraterrestrial sun energy in heating the atmosphere and driving hydrological cycles and weather systems; (ii) Attenuation of sun energy to warm the ecosystem and drive its internal water and mineral cycles; (iii) Energy loss in conversion of sun energy to plant matter; (iv) Energy loss in conversion of plants to herbivores (primary consumers (C₁)); (v) Energy loss in transfer from primary to secondary consumers (C₂). The figures in parentheses in the biological part of the energy chain represent levels for subsidized ecosystems.

Next to the serial connections from plants via herbivores to carnivores, a less conspicuous army of reducers is occupied with the degradation of dead organic material, from both plants and animals (faecal products, dead organic material). These complex food chains are sustained thanks to the same original sources of energy fixed by plants. Of course the above is a picture of a well-known concept in its very simplicity. Many authors have pointed to the fact that real nature is organized far more intricately. Many species are difficult to classify in their position and role and pathways of energy are ‘horrendously complicated’ (Allen & Hoekstra, 1992), as is supported by examples where nutrients pass in or out of the biotic system or the abiotic system at least four times (Fig. 44). Nevertheless the general principles based on the flow of energy and the related laws of thermodynamics are of undisputed and outstanding importance. The ‘laws’ of energy flow are universal and powerful as an explanation for many other features. Since Odum (1983) devotes a voluminous handbook (644 pages) to energy in system ecology we should refer to his concepts and data.

The concept of trophic levels, still receiving widespread support from numerous studies - in spite of all the complexity in real nature - is often used to illustrate the tenability of hierarchic concepts. It certainly has great appeal because it clarifies the constraints made by energy availability (decreasing at each step) for successive ecosystem compartments lined up as cascading systems. A change in constraining factors, e.g. by a drop in primary productivity due to a worsening climate or, vice versa, an increase in productivity due to climatic improvement, or due to a higher input of nutrients caused by e.g. atmospheric deposition of nitrogen should eventually be apparent in all dependent subsystems, including densities of predator species.
Ecosystem homeostasis and development

An important question is whether we are able to detect emergent properties, in addition to the above energy flow characteristics, in ecosystem behaviour which cannot be explained by looking at the constituent units. A first observation is that ecosystems or communities, when the abiotic environment is neglected, can combine a state of relative homeostasis with an extreme complexity and variety while being open to all kinds of flows and disturbances. As an abstract explanation one could refer to Prigogine's work (Prigogine & Stengers, 1981) which states that open systems with throughput of energy often develop and maintain self organization, e.g. expressed in spatial variety, order and some kind of stability. This certainly may be true enough of communities and ecosystems, but conclusions at a more down-to-earth level are still desirable.

In an ecosystem, many subsystems can be discerned which differ considerably from each other and which are functionally interlocked in communities: (sub) populations. Numbers of individuals, performance, life-span and niches differ greatly, as is the case with their links to the abiotic environment. There are many interrelationships between species. Such intricately interrelated subsystems forming a highly organized system would at first sight suggest an inbuilt tendency towards instability. All odds should be on instability if any failure or disturbance were to arise. Ecosystems are not only open to all kinds of disturbances from outside, they even cradle their own sources of instability (e.g. diseases, exponential growth of organisms, competitive forces)! But they conduct their business in a relatively undisturbed manner. This can be described as homeostasis at a community or ecosystem level and explained as an emergent property.

Explanations include the following:
- after an increase in number of a certain species food availability limits further growth
- organisms reproduce effectively after a decrease in number: 'restoration by reproduction'.
- organisms invade or recolonize after local extinction: 'restoration by recolonization'.
- organisms restore balance by predation: an increase in population growth of one species leads to more food availability for predators and an increase in their number which reduces prey numbers. Well-known examples are prey-predator relationships between snow hares and snow foxes or between moose and wolves (Franklin, 1987): 'return by predation'.
- when certain species disappear others, belonging to the same guild (group of species exploiting more or less the same resources) can take over. These are either new species having a comparable niche, or already present species widening their realized niche to exploit what has become vacant: 'balance by replacement'.

These mechanisms may illustrate some major stabilizing forces at work in ecosystems. It is evident that stabilizing forces from distinct origins sometimes cooperate, e.g. in cases where food limitations set constraints on a population of herbivores and concurrently prey-predator relationships do the same from the 'opposite direction' as carnivorous species tend to increase with growing numbers and densities of prey animals. O'Neill (1989) denotes this as a 'two-way-street control'. This might explain why the system as a whole and subsystems as constituent units, exhibit a state of homeostasis. It should be emphasized that the performances of single plant and animal populations added together partly explain (!) ecosystems behaviour in a bottom-up manner, whilst the ecosystem-level as such sets constraints to populations in a top-down manner. Which is a clear example of how these hierarchies work. The above mentioned homeostasis is measured on a relatively short time scale and should not be considered to be eternal. On a longer time axis ecosystems evolve and gradually change both their living contents and their directly connected abiotic environment. Odum (1969; 1971) offers a concise picture of ecosystem development through time and the shifts in energy management, community structure (including species diversity), life forms and life-cycles, nutrient cycling, life strategies and an array of other parameters. One could conclude that ecosystem development (including ecological succession) is grosso modo (!) an orderly, more or less predictable process from pioneer to climax or end stages. It involves a shift in species composition towards more and more specialized species, more closed cycles of nutrients and a gradually increasing independence of abiotic (e.g. soil) parameters.

For our objectives, it is not infeasible to go into more detail or to give room for all sorts of criticism on the general picture, that is sketched above (see also 4.3.3). Evidently, ecosystems feature a great number of feedback mechanisms dampening disturbances from the outside and inside thanks to, and not in spite of, numerous functional relationships. Ecosystem development seems to improve these properties and consequently, ecosystems seem to grow less dependent on some abiotic variables, e.g. by physically changing their environment (soil, microclimate) or by the efficient storage of nutrients in the biomass. As such they detach themselves to a certain degree from abiotic constraints, but at the same time within possibilities conditioned by abiotics. When ecosystems in addition evolve to a structurally varied system, e.g. by vertical layering of herb layers, shrubs and trees, it is clear that new biotopes are gradually created by the system itself, adding to species variety.
Animals and their dependence on landscape structure

Animal species exploit the plant canopy directly and indirectly for various activities such as foraging, drinking, hiding, resting and nesting. They often use various biotopes for different activities. There has been considerable specialization among organisms, resulting in different sets of demands towards the combination of biotope compartments used. This can relate to the nature and number of biotopes, but also to spatial characteristics such as the vertical layering of plant canopies or the horizontal heterogeneity. These features can be expressed in the (vertical) stratification and patchiness (patterns) of the landscape. There is clear evidence that animal species, varying from small beetles to large mammals, display a strong relationship to landscape structure (e.g. Krebs, 1985, Fig. 45; Opdam & Kalkhoven, 1989; Odum, 1971).

Related to landscape heterogeneity are specific ranges (in distance or areal size) of animals exploiting their surroundings. Harris (1984) provides data on average ‘home range size’ and travel distances for mammals. These show ranges of some hundreds of m$^2$ for small voles to some hundreds of thousands of hectares for predators (grey wolves, grizzly bears). Dependence on area size and distance also relates to mechanisms of species dispersal and population dynamics within small habitat patches. Thanks to studies of island biogeography by Diamond (1975) and McArthur & Wilson (1967) there is a growing interest in the relationships between habitat size and the degree of isolation between comparable habitats on the one hand and processes of (temporarily) extinction and recolonization. This has also led to a revival of studies on mainland landscapes that suffer from fragmentation of habitats due to intensification of agricultural use, man-made infrastructure, urbanization, etc. Fragmentation in this case implies decreasing the areal extent of habitats, greater distances between habitats and more barriers for poor dispersers. The guiding principle for both types of studies, the real island situation as well as the pseudo-islands within fragmented landscapes, is that extinction and recolonization are stochastic processes that occur more often where habitat patches are smaller and more isolated. When extinction occurs, recolonization from nearby ‘source’ areas can recharge the empty, ‘receptor’ habitat again (Fig. 46). Chances depend on size and distance of source areas, rates of effective dispersal, size and quality of the

![Fig. 45 Bird species diversity in relation to plant species diversity (a) and vegetative structure (b) (from: Krebs, 1985, after Mac Arthur & Mac Arthur, 1961)](image-url)
empty habitats and some additional factors. Research has thusfar confirmed the hypothesis that island biogeography has its analogies in fragmented landscapes and stresses that:

- there are critical values for minimal population size, dispersal rates, critical distances and relevant barriers differing per species
- there are indications that life strategies, as introduced earlier in this section, referring to concepts described by McArthur & Wilson (1967) and Grime (1979) for plants, are important for the mechanisms at stake. Species belonging to generally stable habitats (e.g. forest species) seem to be less effective in reproduction and dispersal techniques than species belonging to dynamic environments.
- number, size and spatial situation of discrete habitats could be considered at a higher level. Within this context the metapopulation concept proved to be useful. Spatially discrete subpopulations connected to each other by dispersal processes together form a metapopulation. The smaller, more remote subpopulations tend to be more vulnerable for (temporary) extinction processes, the larger ones can act as source areas to refill empty habitats (Opdam, 1987). In fact one could envisage subpopulations, metapopulations, and so on growing to populations encompassing large areas (e.g. continents) as examples of a spatially nested hierarchy. This hierarchy finds its identity in process-functional relationships between populations, based on flows of organisms or other carriers of genetic information, such as seeds.

Social organization

Life, in the case of higher animals, sometimes displays social organization, which could be expressed in hierarchies. Such a social organization sometimes shows a sort of ‘pecking order’ reminiscent of command structures in military or other organizations in human society. This feature can be recognized in herds of herbivores or groups of wolves, but also in colonies of ants or monkey families. Highly developed social
organization may also include division of labour, which means specialization of (groups of) individuals carrying out a certain task. Specialization can even result in seemingly altruistic behaviour. Altruistic behaviour of individuals or groups cannot be understood by individual needs or possibilities alone, but only from its relevance for the higher level (society). Social structures as indicated can be found in great variety in various groups of animals (birds, fish, insects, mammals), for further information, we can refer to the relevant handbooks. Regarding the question of why nature ‘invented’ such structures, Odum (1971) states that such a hierarchical ordering can be explained by assuming that long-term functioning of the group or population must supercede individual short-term profits on the short track. A certain command structure then helps to save energy otherwise spent on intraspecific competition.

3.10 Intermediate conclusions and discussion

Examples from preceding sections support the view that:

- natural systems, and characteristic phenomena belonging to these systems, can generally be characterized by their spatial and temporal scale domains. Such system scaling offers anchoring ground for:
  . delineation of study areas
  . choice of relevant time scales and spatial scales
  . choice of research fields/disciplines
  . coupling of systems based on compatibility in scales
- Analysis of scales confirms that ‘large and slow’ are often positively correlated just like ‘small and quick’. However, one should be aware of anomalies, e.g. the atmospheric system exhibits a large spatial scale and a relatively quick response compared with other systems.
- Most kinds of hierarchies as distinguished in Chapter 2 (process-functional, spatial, temporal, organizational, taxonomic or classificatory) can be encountered in a sometimes kaleidoscopic mix. Process-functional hierarchies, actually expressing cause-effect relationships however are the most appealing as they have the most explanatory power. Other hierarchies are more descriptive and can offer clues for a more causally oriented approach.
- Process-functional hierarchies, both within systems and between systems depend on their relative position in the flows of energy, matter and information (or organisms). ‘Downstream’ systems are dependent on ‘upstream’ systems.
- The ordering of natural systems seen from their position in the flow of energy, matter and information reveals the importance of cascading systems (or serially arranged process-response systems) as a central concept. Flow direction, exchange and storage are key words. Matter and information flows are directly determined by energy flow. Energy flows give the best clues for process-functional hierarchic relationships.
- Earth systems derive their primary energy from sun’s radiation, gravity forces (the earth, sun and moon) and to a lesser degree from the earth’s interior. The source behind exogeneous processes (agents) is the solar radiation driving nearly all cycles in the atmosphere, hydrosphere, pedosphere, biosphere and partly the lithosphere.
- Large physical, more or less fluid systems operating on a global scale as open systems

96
subject to both large input and output of energy and a rotational force develop more or less comparable circulation patterns (cells) that can be interpreted as self organization, e.g. convectional flows in the earth's interior, ocean gyres and the main atmospheric circulation patterns.

- Process functional relationships between systems sometimes reflect considerable asymmetry, whilst other relationships are strictly interdependent in character. Examples of extreme asymmetries are extraterrestrial forces (radiation, gravity from sun and moon) on earth systems. Strong interdependences are found between atmosphere and oceans or between soils and vegetation.

- More than in other (non-living) systems cybernetic properties are involved when distinguishing hierarchic levels in biological or compound systems. Organisms, plants and, to a greater degree animals therefore depend on information flows triggering feedback mechanisms.

- Most systems and systems behaviour reveal the importance of threshold values. Systems react after surpassing these values. This is true for both physical/chemical and biological systems. This could explain, at least partly, why patterns in dependent variables sometimes show sharp boundaries whereas the forcing (independent) variables to which they respond exhibit far more gradual changes.

- Systems possess several buffer mechanisms and buffer capacities. Buffering adds to possible delay in throughput of matter, energy and information i.e. changes in flow rates. Time lag will be greater in i) systems with a larger buffer capacity and ii) in cases where flows run through cascading systems, as these are lined up in series.

- Independent variables can affect dependent variables both directly and indirectly. Climate and climatic change influence vegetation directly but also by changes in hydrology, soils etc. In most landscapes one is confronted with a rather long chain of causes and effects.

- The more dependent systems (e.g. vegetation) are more indicative of properties or changes in independent systems. Indications however are seldom clear.

- Dependence may not be seen as static: some systems show a dependence that decreases in time. Soils are initially highly dependent on parent material, but during their development this dependence attenuates and the interaction with vegetation becomes more important.

- Comparisons of large-scale patterns, e.g. of climate zones, zonal soils and vegetation zones offer excellent contextual evidence for causal relationships. Some correlations however can be deceptive. Patterns are sometimes the legacy from completely different circumstances and periods. Many systems can only readjust to new conditions very slowly.

- Living nature is extremely complex. Data reduction is therefore inevitable. Intelligent, i.e. ecologically relevant, lumping should be based on relationships with abiotic conditions for plants and the flow of matter and energy. For animals, relationships with vegetation composition and structure should enable functional clustering.

- Landscapes are complex, multi-layered systems constructed from geological, hydrological, geomorphological, pedological and biological compartments. Hierarchic relationships can be within and between these subsystems recognized. Insight into temporal and spatial scales of systems and their functional relationships help to specify spatial and temporal features in landscapes. Geology and climate are seemingly large-scale phenomena setting boundary conditions, geomorphology and hydrology are distinctly interrelated phenomena acting on a lesser scale, soils and vegetation being
dependent factors that exhibit even finer patterns. Many landscapes display a 'scaling' of phenomena directly related to this order, a conclusion also reached on more theoretical grounds by O'Neill et al. (1989). Analysing the relationships between systems on their position in flows of energy and matter, their spatial and temporal scales suggests that climate and geology constrain geomorphology, the three together constrain surface and groundwater hydrology, soils are dependent on previous systems, vegetation is dependent on all the factors mentioned and animals are at the end of the list. Animals are especially dependent on vegetation structure. Of course these are simplifications that need to be verified and specified for each landscape.

Somewhat derived from these conclusions it can be stated that going through all examples of hierarchical phenomena in earth sciences and ecology they:
- reconfirm the validity and applicability of the systems approach in describing and explaining phenomena within earth sciences as well as in ecological specializations.
- at least a large portion of the story of hierarchical concepts is a rediscovery of scale.
- the coupling of process-functional hierarchies and the experience that systems and systems behaviour have their specific spatio-temporal domain allow some integration of process-functional, spatial and temporal hierarchies. This aspect will be elaborated in the next chapter (4.2).
4 Hierarchical principles in integrated landscape ecology

4.1 Introduction; linking, ranking and scaling

The core activity of landscape ecology, as discussed in Chapter 1, is integration. In order to integrate knowledge from various disciplines one is forced to identify common ground. This requires an approach which can be indicated by the following key words: ‘linking, ranking and scaling’.

Linking denotes the process of interfacing (= coupling and matching) system variables of landscape compartments such as were dealt with in Chapter 3. It includes i) the identification of vital functional relationships and ii) the selection of parameters to describe functional relationships economically. The choice of parameters is of paramount importance. They are the nuts and bolts which connect systems, that is our models. The challenge is to select parameters that are limited in number and at the same time meaningful. As an example, we can find parameters to connect the vegetation system to the soil system by choosing relevant (sum) parameters, e.g. by expressing basic plant/vegetation requirements or tolerances in terms of soil physics (soil moisture conditions, period of water logging) or soil chemistry (nutrient availability, pH). The challenge is then to select parameters which could also be attached to the soil system (soil profile characteristics, soil maps). Can we do the same for climatic parameters (annual temperature distribution, drought, frost) that are meaningful for plant species or vegetation types (threshold values!) and retrievable from climatic data? Preceding chapters have already given us some clues.

Ranking refers to the analysis of asymmetric relationships (‘what causes what’ or ‘what constrains what?’ in the sense covered in Chapter 2). In the most simple manner this could be done by qualitative pairwise comparison, resulting in the arrangement of a pair of systems and system characteristics according to their relative dependence or independence in complex systems. Repeated pairwise comparisons could provide some insight into how complex systems, consisting of more than two (sub)systems, operate.

Scaling implies the identification of spatio-temporal domains of phenomena and from there a conscious choice of scales. Landscape phenomena should be analysed on their characteristic scale domains (geographical extent, spatial variability, frequency, response time). Directly related is the choice of the system boundaries (the size or extent of the area and the delineation) and of the spatial resolution (size of minimal map units, pixel size or grain). All these choices should be based on the foreseen applications and the landscape properties themselves. Special attention is required concerning the question of how to combine differently grained data from various disciplines. Of course one needs to select relevant parameters for each scale.

Linking is, of course, a very general task when studying systems and building models. Therefore it is not typical of hierarchical approaches, but both ranking and scaling are issues directly connected to hierarchical approaches (process-functional and spatio-temporal hierarchies respectively).
The aim of this Chapter is to discover whether hierarchical concepts from Chapter 2 and experiences from Chapter 3 could contribute to landscape ecology as an integrated approach. The adjective 'integrated' when linked to landscape ecology could be interpreted as tautology. However, since there are numerous, almost mono-disciplinary studies at landscape scale, we take integration of abiotic and biotic phenomena as a criterion to select studies trying to bring hierarchical principles into practice (4.2). As we consider hierarchic thinking to be promising for future studies, an attempt is made to offer some background to the never-ending debate on stability-diversity relationships (4.3). We conclude this Chapter by focusing on the connection between landscape-ecological insight on the one hand and a framework for decisions on the other. Reasons for this are i) the fact that landscape ecology is an applied science and ii) the fact that hierarchical approaches could apply to both fields and should be connected wherever possible (4.4).

4.2 Some examples of hierarchical approaches in integrated landscape ecological studies

We have taken mainly Dutch studies to illustrate the possibilities, challenges and pitfalls: a study of the Dutch coastal dunes (Bakker et al., 1981), and - conceptually related - a study on brook systems (Everts & De Vries, 1991), secondly, the approach followed by Frissel et al. (1986) in which spatio-temporal hierarchies in river systems were operationalized, and thirdly attempts to connect spatial and temporal scales to dominant processes in order to design a spatial hierarchy of geographical units for environmental policy purposes (Klijn & Udo de Haes, 1994).

Landscape ecology of the Dutch coastal dunes

Bakker et al. (1979; 1981) executed a landscape ecological survey of the Dutch coastal dunes (40,000 ha) resulting in thematic and integrated maps, cause-effect descriptions and recommendations for planning and management. To integrate pattern and process data on climate, geology, coastal influences, geomorphology, groundwater, soils and vegetation a so-called hierarchical model was used to arrange data and ideas. Originally, this conceptual model (i.e. not a simulation model) was inspired by the concept of 'spheres' as suggested by Teilhard de Chardin (1959) and upon by Van der Maarel & Dauvellier (1978; Fig. 47). The model concept of Bakker et al., however, was in fact based on the analysis of matter and energy flows between subsystems or partial complexes ('Teilkomplexe' cf. Richter 1968 a, b) and relative dependences and independences between these partial complexes (e.g. groundwater, soil, vegetation). To determine such relationships a (repeated) pairwise comparison (see also Saaty, 1980; 1992; 4.1) between these subsystems was carried out using eight criteria:
- the 'sine qua non' condition: the existence of a subsystem directly depends on the existence of another system (porous rock or sediments > groundwater)
- direction of energy flow or energy potential (e.g. solar radiation and potential kinetic energy respectively)
Fig. 47 The concept of spheres (from: Van der Maarel & Dauvellier, 1978)

- direction of (potential) flow of matter (it was noted that energy flows direct flows of matter)
- in local or regional cycling of matter (e.g. nutrients): position of sources and sinks.
- Scale - or reservoir proportions: small-scale, local subsystems generally depend on large-scale systems with greater storage of matter or energy
- Data and insight into genesis/evolution (e.g. wind as an agent creating geomorphology)
- Pattern relationships mirroring dependency between systems (e.g. climate zones > vegetation zones (This acts as a complementary criterion and is in fact a correlative and not necessarily a causal relationship)
- Insight into process-effect relationships from observation: what influences have a documented effect on dependent systems

The model was composed by ordering and ranking several processes and subsystems in a general scheme, from which a more specific hierarchic model for coastal dunes was derived as shown in Fig 48. Subsystems (central column), natural processes and man-induced processes are ranked according to their position in functional hierarchies. Going in a top-down direction the model shows a shift from the more independent towards the more dependent subsystems and shows that natural or man-induced changes inevitably affect lower ranked subsystems. It also shows that influences in the opposite directions are possible, but these normally have a less important or merely local effect on higher levelled subsystems. The model was used to i) design map legenda’s and facilitate the procedure of regionalization, ii) to clarify cause-effect relationships from both natural or man-induced origins (Fig. 49; impact assessment) and iii) to clarify the order of appearance of (sub)system descriptions in the report. Studies very similar to the above have been executed in other, Pleistocene landscapes in the Netherlands (Bakker et al., 1981), whereas the model also served as an unifying concept in coastal dune studies in general.

When evaluating this approach it should be stressed that the model is primarily a conceptual model, based on general notions (expert judgement) whereas quantification by means of mathematical descriptions in a formalized model structure capable of acting
as a computerized simulation model has not yet been. The model is designed for coastal dunes, i.e. a specific landscape, where asymmetrical relationships (e.g. relief > groundwater > soil > vegetation) are relatively clear. Other landscapes exhibit interdependencies, e.g. between soil and vegetation due to succession and (initial) species composition more often. This is illustrated by the study carried out by Vos & Stortelder (1992) in Tuscany (Italy), stressing the influence of forest vegetation on soil formation and more recent comparable studies on forest ecosystems in the Netherlands (Hommel et al., 1993).
climate: changes in temperature, precipitation, evaporation, storm regime

coastal processes: erosion, accretion

groundwater: changes in quantity and quality

vegetation: flora and vegetation changes

climate: changes in temperature, precipitation, evaporation, storm regime

coastal processes: erosion, accretion

geology: geological configuration

relief: primary and secondary dune formation

groundwater: changes in quantity and quality

soil: mineralization, humification, leaching

vegetation: flora and vegetation changes

Fig. 49 Cause-effect relationships in the Dutch coastal dunes hierarchically ordered (from: Van der Meulen, 1990 after Bakker et al., 1981)

The model described by Bakker et al. (1981) does not include animals and relationships with vegetation or other subsystems. It also lacks a specification of spatial relationships (chorological dimensions), such as those between ecotopes. Zonneveld (1985) and The Working Group Theory (1986) commented that the ranking developed for coastal dunes would probably differ from landscape to landscape and would also depend on the scale.

Landscape ecological study of stream valley (brook) systems in a Pleistocene area in Drenthe the Netherlands (Everts & De Vries, 1991)

This study focused on vegetation patterns and processes in two stream valleys as related to, and determined by, abiotic conditions such as geology, geomorphology, hydrology, pedology and the applicability of this knowledge in a decision support model. The authors followed and adapted the model concept of Bakker et al. (1981) by including landscape-specific features, e.g. by adding information on salt-tectonics and by the importance they attributed to the microclimate (Fig. 50). In their approach, more attention is paid to groundwater hydrology, especially the water quality aspects and related to this determining factor - flow direction of groundwater in deeper and shallow water systems. This approach was presumably influenced by the systems approach elaborated upon by Tóth (1963) and Engelen and co-workers, as explained in Section 2. Another striking difference is that this study had to take into account a larger time frame than Bakker et al. (1981) needed to do in their study of the very recent Holocene landscape of coastal dunes (originated after approximately 1000 AD), since natural and man-induced processes have affected the area for a considerable longer period.
Fig. 50 Hierarchical model for brook systems in a Pleistocene area in the Netherlands (from: Everts & De Vries, 1991)

Case study of hierarchical classification streams and stream habitats (Frissel et al., 1986)

These authors studied streams and stream habitats and designed a classification that
is systematically hierarchic. They identified relevant abiotic and biotic phenomena in and near streams and positioned them in a spatio-temporal framework. The resulting classification was a nested hierarchy with the following five levels: stream systems > stream segments > reaches > pools/riffles > micro-habitats (see Fig. 51). As Fig. 51 shows, spatial scales (expressed in metres) and time scales (in years) differ for each level. A set of typical events in the evolution of the (sub)system and processes that govern developments were defined for each level. They attempted to indicate what were considered to be the major driving forces or decision variables for each level.

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![Diagram of stream system hierarchy](image)

**Fig. 51 Hierarchical ordering of stream habitats (from: Frissel et al., 1986). Spatial and temporal scales indicates as well as dominant processes**
At the stream systems level, geologic/geomorphic history and climate were dominant. Typical indicators of this level are the slope and shape of the longitudinal length profile and the drainage network structure (pattern and density of streams and junctions). At the next-lower level of segment systems (bounded by junctions) the lithology and structure of bedrock proved to be decisive, next to the slope of the river bed, the relative position in the network and the valley side slopes. Within this level the next lower level of so-called reaches was discerned. This 'least' physical unit mirrors characteristic ranges of bed materials. Determinants are watershed events, mass movement from valley sides, bank material, large obstacles (e.g. trees) and riparian vegetation. Typical time scales vary from decades to more than a century. A smaller subsystem is the pool/riffle system with characteristic bed topography, bedform stability, depth and velocity of water etc. The smallest unit relates to micro-habitat: patches that are homogeneous in substrate, water depth and velocity. These are disturbed annually and their characteristic development time is counted in days, weeks or months. Determinants are geology, climate, vegetation, network position, land use and slope.

Evaluating this study it can be stated that it offers a clear and systematic classification which summarizes knowledge of driving and decision variables specified for spatio-temporal scale domains. It emphasizes the dominant role of abiotic processes from the highest to the lowest level. It gives clues for research methods as well as land use planning and management. The example also illustrates the fact that constraints from higher levels remain relevant for lower levels, emphasizing an essential property of river systems. Large-scale events, conditioned by climatic events, can affect small-scale features rather quickly due to the high transport rates of river systems.


Environmental problems in the Netherlands, affecting human environment and biodiversity, can be attributed to eight major threats: climatic change, acidification (by atmospheric pollution), toxification, over-manuring, desiccation (by lowering of the groundwater tables), loss of biotopes (e.g. by building), fragmentation of habitats (e.g. by infrastructure) and disturbance (of animals by man's activities). The above mentioned study departs from the model described by Bakker et al. (1981), although extrapolated to other areas and a larger scale domain. The analysis is aimed at distinguishing relevant spatial and temporal scales related to the problems already mentioned, taking into account that agents responsible for transport and deposition differ for specific spatio-temporal domains: some problems are directly connected to atmospheric transport, others to transport of nutrients by surface waters, again others are rather local in character. This notion of spatial scales and typical processes has been combined with an assessment on what systems such environmental influences have their primary point of impact. Secondary effects were assessed on the basis of knowledge of cascading systems as explained earlier. The outcome of this qualitative approach is summarized in Fig. 52. The hypothesis on the dominance of certain processes on a certain spatial scale was used to present a geographical analysis of the Netherlands resulting in a regionalization into units at eight levels. The distinction in (spatially) nested units was terminologically inspired by Canadian approaches (e.g. Bailey, 1981). As shown each level is dominated by a different set of influences.
Fig. 52 Hierarchical ordering of environmental processes, their primary impact and subsequent chains of effects in landscape components (from: Klijn, 1994)

When evaluating this approach, which was rather ambitiously presented as a hierarchic ecosystem classification, it can be stated that the approach of Bakker et al. (1981), designed for Dutch coastal dunes on the basis of a rather thorough analysis of processes and relationships within this landscape, was brought into a system for all kinds of landscapes and a greater scale domain.

The approach leads to a system declaring certain levels in scale dominated by certain processes, irrespective of the type of landscape. It can be seen as comparatively theoretical as it is based on expert judgement rather than empirically founded relationships.

Comments

As more general comments on the above examples we can introduce the following points:

- the examples are biased, because mainly they relate to Dutch landscapes and Dutch territory. However, examples from other countries in which hierarchical principles are operationalized are relatively scarce and usually restricted to a few landscape components, whereas our challenge does not just relate a few slices of the cake, but the entire cake. Nevertheless there are classical studies that, without even mentioning the word hierarchy, have used intuitively or well-considered analogous approaches
to describe and explain landscape ecological phenomena (e.g., Zonneveld, 1960; Borman & Likens, 1979).

- the examples have in common the fact that hierarchical thinking is expressed in conceptual models, directly referring to knowledge of systems behaviour and systems interactions in which flows of energy and matter are considered decisive. These notions are usually generally accepted, sometimes in a more hypothetical sense, but altogether considered to form useful working hypotheses (Bakker et al., 1981). Attempts to design more formalized and quantified complex models based on the general concept have hardly been made, although systems analysis on parts of the ecosystem (e.g., groundwater hydrology) certainly yielded quantification and computer simulation models (e.g., Bakker, 1981; Stuyfzand, 1993). It is doubtful if any attempt to construct a really integrated quantitative computer model by means of a complex set of mathematical equations covering all relevant landscape processes and patterns would be beneficial. The advantage of a conceptual model is its relative simplicity, which promotes communication and discussion.

- Most approaches relate to both abiotic and biotic systems, but animals and their chorological characteristics are still insufficiently included. This would ask more insight into biotope requirements, including landscape heterogeneity and chorological relationships very few attempts have been made to relate abiotic data to vegetation composition and structure and its development during time and from there to animals (presence and densities). Harms et al. (1991; 1993) designed a GIS-based knowledge model predicting such processes in a large region in the Netherlands.

- Whereas Bakker et al. (1981) left hierarchical relationships rather undefined for scales within their study area, later studies (e.g., Verdonschot et al., 1991; Frissel, 1986; Klijn & Udo de Haes, 1990) tried to indentify scale-related dominance of certain processes. This seems to be a promising avenue, relevant to purposeful and practical classifications and related mapping of systems. It allows a connection between process-functional hierarchies on the one hand and spatio-temporal hierarchies on the other.

4.3 Stability and diversity of ecosystems from a hierarchical point of view?

4.3.1 Introduction

Whereas the preceding sections gave examples emphasizing the conceptual aspects of hierarchical approaches in landscape ecology in different areas and applications, this section aims at ways of operationalizing hierarchic thinking. We have chosen an important and sometimes controversial subject: stability and diversity at landscape level.

We intend to show i) how hierarchical concepts help to realize the spatio-temporal domains and ii) how process-functional hierarchies help to identify cause-effect chains involved in landscape dynamics.
4.3.2 Stability-diversity relationships

Probably one of the most pivotal, difficult and least productive discussions in ecology and its applications relates to the assumed relationships between ecosystem (or landscape) stability and (species or community) diversity (see for an overview e.g. Van Dobben & Lowe McConnell, 1975; Krebs, 1985; Klijn, 1987). Discussions focused on the question of whether stability promotes diversity in plant and animal species or - inversely - whether diversity could add to stability. Debates were plagued by considerable confusion, mainly because time scales and spatial scales were undefined! (see also Van der Maarel, 1993). However, the issue did not lose its vitality, since it relates to the roots of landscape management. Nature protection and nature management are constantly in search of criteria to judge whether stability or instability (natural or artificially triggered) should be allowed or even promoted to retain, restore or enlarge biodiversity. The fact that debates between the ecologists were so unproductive due to unspecified spatio-temporal contexts can be illustrated as follows: on a short time scale and for a limited area any natural disturbance can be considered catastrophic. On a larger spatio-temporal scale however a sustained biodiversity most likely depends on the very occurrence of such smaller scale events. Large-scale, long-term stabilization leading to a dominance of certain successional stages and related species would eventually lead to a decrease in biodiversity. Without defining spatial and temporal scales, assessments as given above are seemingly in conflict. Only by specifying spatio-temporal scales can paradoxes be revealed. A growing awareness of scale factors and their practical importance can be observed with respect to forest fires (e.g. Urban et al., 1987; Turner et al., 1993), the influence of sand blowing in sand dunes (Bakker et al., 1981; Klijn, 1987) or fluvial dynamics (Schumm, 1988, Amoros et al., 1987; Frissel et al., 1986; Rademakers, 1993).

Although a change in management strategies can be observed, many management plans still aim at the conservation of specific successional stages irrespective of long-term developments over larger areas. As a result, efforts and management costs can be high - and even tend to increase with time whereas an approach that engages natural processes in a larger scale domain would be both more effective and cheaper (e.g. Risser, 1992; Scott et al., 1992; Wali, 1992).

4.3.3 How to assess disturbances?

With some exaggeration one could state that we have only recently left behind a period during which the ‘real and desirable nature’ was believed to be the prerequisite of a system in equilibrium. All other situations were considered to be either prior stages on their way to equilibrium or the result of smaller or larger disasters that should be followed by recovery. These ideas were fed by concepts on ecosystem development towards a more stable mono-climax through several successional stages, whereas succession pathways were considered more or less simple (Odum, 1966). Nowadays, ideas have changed as it is widely accepted that i) many changes in landscapes are quite natural and far more frequent than previously thought ii) should speak of equilibria instead of one equilibrium. Some authors even deny the existence of equilibria and
prefer to envisage nature as constantly changing iii) the awareness that successional pathways generally have a multiple character (Horn, 1976) and mono-climax concepts should be replaced by poly-climax concepts and iv) the appraisal of changes or disturbances in landscapes with respect to their effect on biodiversity should be considerably adjusted. Acceptance among ecologists and land managers of the positive effects of disturbances in addition to the negative effects is growing, also for the less familiar events. It is the degree that counts.

Landscape dynamics are changes (cyclic or non-cyclic) in landscapes. Immediately the question arises of what to call a change and how to define it in order to make it tangible and operational. This proves to be a matter of assessing the possible effects and a matter of scale in the first place. Some changes are so widespread, frequent and familiar to the living components of (eco)systems that they can be considered as ‘normal’ or ‘business as usual’ and therefore neglected. Examples are day and night cycles, tidal movements, seasonal dynamics. Nature is completely adapted, e.g. by the physiology of plants and animals, in species composition and behaviour (for instance in bird migration or hibernating strategies of animals). Abiotic components can be also adapted to regular dynamics as in the case of the morphology of tidal channels. When systems are adapted to a certain regime of dynamics, a shift to a less dynamic situation would also unbalance the system, as much as an increase in dynamics would do! It follows that when we want to focus on landscape disturbances, they should be defined more thoroughly. One could do this as follows: ‘any relatively discrete event in time that disrupts ecosystem, community or population structure and changes resources, substrate availability or the physical environment’ (White & Picket, 1985). This definition excludes very slow or gradual changes such as plate tectonics in geology but also more rapid processes such as natural succession, which sometimes changes ecosystems within a space of few years. Neither of these changes could be classified as a discrete event. Thus it is clear that any operationalization of disturbance phenomena in landscapes demands further specification of (eco)system, temporal and spatial scale (see also Van der Maarel, 1993). An old tree collapsing in a forest could destroy bryophyte communities or a woodpeckers’ nest, but this event hardly affects the forest as a whole and certainly has no long-term effect on the forest.

Disturbances in landscapes have many shapes. From provisional lists of White & Picket (1985), Risser (1987) and Wali (1992) we extracted items such as fire, hurricanes and storms, the working of ice and frost, droughts, water level dynamics (including flooding), fluvial erosion and sedimentation, coastal erosion and progradation, wind erosion and deposition, landslides, lava flow, diseases, predation, immigration, introduction of new species (sometimes considered as pests), and typical man-induced processes such as mining, drainage, regulation of rivers, clearing of land, waste disposal, use of biocides, air, soil or water pollution by toxic or acid-forming substances or nutrients, building, infrastructural works and so on. Such lists could be extended and detailed almost endlessly and this confirms the earlier conclusion that ranking and ordering according to spatial and temporal scales and types of impacts is necessary. Ordering criteria are scale (extent), frequency and duration and intensity or severity. As disturbances can occur in various places in landscapes during a certain time it might be worthwhile including a parameter that describes the way in which disturbances spread in space and time, for instance by defining the rotation period: the time needed for a
complete area to become affected by a disturbance (e.g. forest fire). Of course this is the average time: some parts could be affected a few times, others will never be affected.

So far for disturbances in general. Hierarchical principles could, in our opinion, be helpful in some of the following points of interest (indicated by an asterix):

- * by defining scales of disturbances in space and time
- * by defining the point of impact: which landscape component is affected first (forest fires affect the vegetation layer, landslides primarily affect soils)
- * by analysing the cascade of effects through dependent systems that are lined up serially. Water extraction primarily affects groundwater systems, resulting in changes in soil physics and chemistry, eventually affecting vegetation.
- by determining whether or not effects are reversible
- by defining recovery time for the variable(s) in focus (e.g. vegetation)
- * by assessing relaxation times, using knowledge of the cascading systems
- by relating natural disturbances to events in history: are they familiar to (eco)systems or not?
- * by evaluating effects on biodiversity on a range of scales: a disturbance could be assessed as negative on a small scale in time and space and at the same time as positive on larger scales. The latter could be illustrated by the contribution to abiotic diversity of geomorphological disturbances, eventually leading to biodiversity or the reset of succession after forest fire adding to diversity as well
- by classifying impacts of human activities according to their resemblance to natural events (especially with respect to naturalness and point of impact).

A promising approach in which to operationalize some of these aspects on a landscape scale was put forward by Turner et al. (1993), who selected the following major factors (the simplified presentation is ours!):

1. disturbance frequency (events per time unit, e.g. one forest fire per 100 years)
2. rate of recovery from disturbance (in years, e.g. 75 years to reach a comparable stage in forest development as before)
3. size or spatial extent of disturbance (areal unit, e.g. in hectares or square kilometres)
4. size or spatial extent of the total area or landscape in which disturbances occur or could occur.

By combining 1 and 2 in a ratio (T) expressing the ratio between disturbance frequency and recovery time an indication of recovery chances is given, by combining 3 and 4 in a ratio (S) the affected area proportional to the total area is indicated. Both indicators combined give a measure of how areas experience certain disturbance regimes. The next step in their reasoning is to evaluate effects of different regimes on landscape variance. Figure 53 shows the outcome of this, so far theoretical, exercise by indicating where ecosystems become unstable or crash (too many disturbances over too large areas), where ecosystems tend to develop towards mature stages over large areas leading to, sometimes, slow variance and intermediate stages where variance is promoted by some degree of disturbance.
It can thus be concluded that landscape disturbances could be approached using hierarchic insights. Process-functional hierarchies offer insight into cause-effect chains, spatial and temporal hierarchies help to realize the importance of scales. Key words are the identification of the point of impact, extent and frequency relative to the relevant area, types of ecosystems and recovery time and above all insight into cause-effect chains. Both research and landscape planning and management could profit from this awareness.

4.4 Decision making; intermezzo (3)

4.4.1 Introduction

Landscape ecology is primarily considered to be an applied science, meant to give clues for well-considered decisions. It is therefore tempting to find out whether scientific hierarchical approaches could be connected to the process of decision making.

Practical challenges for landscape ecology directly relate to land use planning and land management, either for direct human profit or for the sake of biodiversity (see 1.3). Both planning and management embrace decisions on what to do or what not to do with a piece of land. As indicated earlier, decision making reflects - either almost intuitively or in a well-considered way - a form of hierarchic thinking. In its absolute simplicity, decision making should work 'from the greater to the smaller', long-term goals should be in context for short-term affairs and the priority of decisions should reflect common sense in terms of 'first things first'. It is striking how much these notions as expressed in plain language, reflect hierarchical thinking.

These aspects could be elaborated upon for our goals by defining spatio-temporal scales in the first place. The size of the area involved can vary from a small management unit
such as a parcel within a farm to a large portion of a whole country where physical planning tries to design an adequate lay-out for a variety of functions. Time frames may also differ considerably: a farmer can decide about ploughing, seeding and cropping on an annual basis, physical planning aims at time horizons of up to thirty years. In the same way as for the spatial extent and duration of natural phenomena, a spatio-temporal positioning of decisions could be achieved (see e.g. Fresco & Kroonenberg, 1992). In a landscape-ecological context these decisions should relate sustainable land use or nature conservation goals. Decisions could aim at the complete spectrum of purely natural processes towards man's activities, founded on knowledge-based assessment of what is desirable or tolerable (Bakker et al., 1981).

Decisions should be based on well-defined goals: what would be achieved implementing these decisions? Goals can vary from higher production rates in agriculture to the designation of a stretch of land for a new function (e.g. outdoor recreation or nature rehabilitation) but goals could also relate to measures which help to avoid foreseeable risks such as erosion, environmental degradation, climate change. How succesful decisions are depends on many factors, which could be arranged in i) a good diagnosis of actual or oncoming problems or opportunities ii) good insight into how things are interrelated iii) a well-considered choice of measures or instruments that are effective, efficient and without adverse side-effects and eventually iv) enough 'span of control and steering power' to implement these measures suited to the extent (scale) of the problems or goals and enough force and an adequate reaction time to reach the goals anyway.

4.4.2 A hierarchical approach of decision making

Whether or not (semi-)natural systems are hierarchically structured, decision processes can be approached following hierarchical principles (Mesarović et al., 1970; Saaty, 1990; Vargas, 1990; Haimes, 1977). We give a brief introduction about general principles before trying to connect these to hierarchical features which are emerging from landscape ecological studies and related disciplinary fields.

We will start from the position that rational decisions are necessary to fulfill future needs and/or cope with actual or foreseeable problems. The idea is that decision making is a process that could be broken down in a hierarchy of goals. The main, superior goal would be formulated in general terms and put on the highest level, subgoals would fit within the main goal and support it, and on lower levels more specific goals could be formulated and so on. When side-stepping technical discussions on the exact definitions concerning types of hierarchies in decision making, it is crucial to indicate three common features (free after Haimes, 1977):

- Higher level decisions are concerned with a larger portion or broader aspects of the overall system
- Higher level decisions have longer time horizons; they are concerned with longer range behaviour
- Higher level decisions have priority of action over lower level decisions.

So far the general notions from decision theory, which shows that its concepts often
include spatial hierarchy, temporal hierarchy and implicitly a hierarchy in complexity in a fashion that higher decisions levels aim at larger, more complex and long-term systems.

4.4.3 Elaboration

To facilitate a rational design of a multi-layered or multi-levelled hierarchy in decisions the following steps are considered necessary:

1. Problem analysis in a qualitative, 'black box' approach:
   - size: spatial/geographical extent; are there logical boundaries?
   - rate: speed of processes; nature (increasing?)
   - time scale?
   - threats/opportunities?

2. Further problem definition (a 'grey or white box analysis')
   - cause-effect chains: what are original causes; what are the routes of effects?
   - feedback mechanisms (positive or negative feedback)?
   - critical thresholds?
   - uncertainties (how serious for subsequent action)?
   - foreseeable side effects?

3. Goal setting:
   - general, imperative goals: what to aim for, what to avoid as the ultimate goal?
     What are the boundary conditions from other aspects?
   - derived goals at lower levels: what to aim for the area A, period B, variable x or y?
   - stratification of goals from several areas of interest (for this phase a method of pairwise comparison can be useful; see Mesarovic et al., 1970; Saaty, 1990).

4. Choice of instruments/measures:
   - political/legal
   - behavioural/socio-cultural
   - technical
   - financial (e.g. subsidies)

5. Definitions of feasible alternatives (including combinations of measures)
   - relative effectiveness
   - cost-benefit ratios
   - uncertainties

6. Implementation
   - monitoring the achievement of achieving goals/deviations
   - adjustment of goals and/or measures
   - how to cope with unforeseen behaviour of the system/external disturbances?
An illustration of how problems or goals could be set to their intrinsic time and spatial scales and how interventions and responsible authorities or organizations could be ascribed is derived from Delft Hydraulics (1992) dealing with coastal environments. This scheme (Fig. 54) shows which interventions or techniques could be effective at which level and who should be involved and responsible for initiatives and execution of decisions.

An interesting example to illustrate how the perception of problems could gradually evolve towards a growing awareness of scales in time and space (which are the exponents of hierarchies) and insight into cause-effect chains indicating to independent, constraining variables which are decisive for the more dependent variables is the rather recent shift in goals and strategies in nature conservation in the Netherlands. The decline in species and biotopes has led to scientific and public uneasiness and alarm since the beginning of the century, causing counterforces from non-governmental organizations as well as - later - from the government. The first strategies and concrete measures were aimed at species protection (e.g. by legislation on hunting) and biotope safeguarding, by legislation or by purchase of land. A further phase introduced the notion that external regional influences, e.g. in water management (lowering of water tables, pollution of ground and surface water) proved to have major negative effects, later followed by ideas that long-distance threats could also be serious in the case of atmospheric deposition of acids, nutrients or toxic substances. It is remarkable how major threats like these are rather-large scale (regional, national, international). Meanwhile, the situation of nature in agriculturally managed areas witnessed severe deterioration caused by changes in...
in management at farm level and reallocation plans, which led to large-scale land use systems. Driving forces for these developments were technology, national policy and above all the impact of EU-policies. Synchronously scientific knowledge emerged that small, isolated nature areas amidst a 'cultural desert' became subject to the menace that vulnerable species would extinct locally, whereas recolonization chances decreased simultaneously (see 3.9).

As usually policy making, legislation and concrete measures tend to suffer from a considerable timelag, but policies and proposed measures have apparently shifted from a small-scale, short-term level (framed in a somewhat reactive and defensive strategy) towards a higher, even global scale, long-term strategy that is more offensive with respect to different land use. In short, there has been a change in attitude towards an upscaling and a shift from effects to causes. The latter explains the dominant interest in abiotic boundary conditions for nature conservation and rehabilitation which requires a large cleaning-up operation of water, air and soil in international, national and regional policies.

The upscaling also forces criteria to be set at international level, which may overrule or at least constrain national or regional criteria for goal setting (Wolff et al., 1989; Bink et al., 1994).

To summarize, it is evident that desired applications of landscape ecology should suit the process of decision making. Both fields could profit from hierarchic thinking as it helps to arrange natural phenomena and related processes on the one hand and decisions on planning and management on the other within a comparable framework. Another observation may be that problems of environment and nature require a serious upscaling (with regard to both spatial and temporal scales). It is inevitable that (landscape) ecology should follow.
5 Concluding remarks

'Nature doesn't come as clean as you think it'
(A.N. Whitehead, cited in Chorley & Kennedy, 1971)

'We always pay for generality by sacrificing content and all
we can say about everything is about nothing' (Boulding, 1965)

5.1 Introduction

Since we presented more specific conclusions on hierarchical phenomena in preceding
Chapters this Chapter is used for a discussion on eight more general or even
philosophical questions.

5.2 Is hierarchy theory really a theory?

Hierarchic thinking is often presented under the rather pretentious flag of a new theory.
Although we are convinced advocates of hierarchical attitudes in science and more
specifically landscape ecology we feel somewhat hesitant to use the word theory. For
this reason the sub-title of this study refers to the 'unbearable lightness' of hierarchy
theory! Our objections are twofold. Firstly, the General Systems Theory offers context
and firm support for hierarchical approaches. Secondly, a theory should earn its
legitimacy in its role as a breeding ground for new hypotheses. However, most treatises
on hierarchical theory acknowledge its shortcomings in this respect (O'Neill, 1989:
'For many ecologists hierarchical considerations appear more as a conceptual framework
than as a predictive theory'; see also Steele, 1989). The outcome of the present study
supports this criticism in that hierarchical principles are primarily useful to order and
rank (i.e. organize!) data and insight into relationships, well aware of scales, in a
comprehensive way. It is a conceptual framework. The fact that hierarchical principles
are, in the first place, tools to organize or reorganize existing or new knowledge is no
reason to underestimate their value. They help to distinguish between large and small,
the inside and outside of systems, the long-term and the short-term. They help to focus
on the right level while still realizing the relevance of next higher and next lower levels.
In short, they help to create or increase awareness, with benefits for better and more
economical research. They support well-considered choices in the research itself and
improve communication among scientists working on different 'levels', or equally
important between scientists and decision makers.

And, last but not least they may help to make decisions that are more effective and
less expensive. In response to some negative qualifications on hierarchic approaches
('old hat') it may be enough to quote Koestler (1967) who retorted that 'old hat, handled
with some affection, can produce lively rabbits'.
5.3 The need to restrict the concept?

How hierarchic notions are used in daily life and common parlance or in several branches of science, was explained in Chapters 2, 3 and 4. The picture emerges of a loosely defined term that is (too) easily applied in all cases where phenomena display any asymmetrical relationship. These may belong to abstract or concrete systems, taxonomies, command structures, social structures, spatially nested systems, non-nested cascading systems where flow directions are governing dependence, or to increasing degrees of organization.

Such a broad conception of hierarchies has some charm and certainly exhibits a metaphorical power but impedes scientific use. Our conclusion for applications in landscape ecology is to focus primarily on functional hierarchies sensu lato (see also Allen & Hoekstra, 1992). Functional refers to i) relative dependence of units on other units with respect to their position in flow directions for energy, matter and organisms (i.e. process-functional and usually connected to cascading or process-response systems) and ii) to degrees in biological organization in which higher organizational levels display more regulating mechanisms by means of feed-back processes than lower levels.

In addition, and in connection with these process-functional and organizational hierarchies, a hierarchic ordering of spatio-temporal domains proved to be a useful if not compulsory part of landscape-ecological research.

5.4 A main division in hierarchies in landscape ecology?

As stated above one could find reasons for a simplified lumping of hierarchies relevant to landscape ecology:

Process-functional hierarchies

This category could be explained as a set of hierarchies directly linked to flows of energy, matter and organisms in cascading systems or in a serial configuration of process-response systems. This type of hierarchical ordering is close to a more conventional concept of cause-effect chains. Output from ‘upstream’ systems and decision variables (e.g. filters) determine the constraints as well as the possibilities (degrees of freedom) for dependent systems that physically (spatially) do not belong to the former system. Systems, distinct and spatially separated units, are in that case non-nested. Dependences are ruled by flows of energy, governing also the main flows of matter. These hierarchies are common within and between abiotic systems and between trophic levels. Convincing examples are given by Chorley & Kennedy (1971) for physical geography and by Odum (1983) for biological systems.

In our study we went through disciplines occupied with partial systems (e.g. trajectories in surface drainage systems) as well as integrated approaches of landscapes involving flows between landscape components. We noted, where hierarchical ideas were practised,
that they differed considerably in nature. *Common ground was observed in the way disciplines used the analysis of flows of matter, energy or organisms to determine what forcing functions, decision variables and related constraints are and what variables should be considered as dependent. The system theory provides the common language.*

**Organizational hierarchies**

This category refers to organizational features as sometimes present in physical systems but more often, and in many forms, in biological systems. The latter exhibit many *feedback mechanisms, thanks to cybernetic properties,* between the various entities of the systems. It may be questioned on beforehand whether it would be productive to rigorously separate this category from the first mentioned one dealing with flows of matter, energy and organisms. It is usually true that cybernetic mechanisms in living nature are 'at all levels' directly or indirectly involved with the regulation of flows through the system. From this standpoint a sharp boundary is rather theoretical. But, in biology we are dealing with processes that are sometimes completely different from the physical and chemical world and essentially *the emphasis here is on information flows:* signals of any kind leading to goal-oriented performances. These form a world of their own, and, as such, a separate treatment is justified. It is evident that the operationalization of types of hierarchies is extremely difficult. Organizational hierarchies in nature are easy to recognize but difficult to grasp. To quote O'Neill (1986), their appeal is more intuitive than by their operationalization. Nature is so complex and multiform that one hierarchical concept to cope with all this variety is not feasible. It would probably be far more practical to direct our attention to certain groups of phenomena to discover what can be achieved by hierarchic thinking.

It depends on definitions and the way we delineate systems whether this category refers to nested systems, in which smaller (and sometimes simpler) entities are part of a larger (and sometimes more complex) whole. Consider a community as a compound system exploiting a certain area, containing smaller entities that are therefore nested. The performance of the higher level unit exhibits other, extra characteristics compared with the smaller entities (e.g. populations). These characteristics can be explained partly by mathematically integrating and averaging static and dynamic features of lower level units (leading to averaged, slower behaviour). Another part of the explanation, however, should be based on specific functional relationships between units giving added value (remember the performance of the whole combustion engine instead of its constituent parts). These are the so-called emergent properties (see 2.4) encountered when looking upwards along the hierarchical ladder and recognizing increasing degrees of organization. Looking downwards along the same ladder it is clear that the higher level sets constraints or boundary conditions towards lower level entities. Examples can be found in the way communities set limits to the population increase of one species due to prey-predator related control mechanisms or how animal populations or groups (e.g. herds) set conditions for individual behaviour. These types of hierarchies can be characterized as being self-inflicted. This also raises the question of whether we should speak of top-down or bottom-up hierarchies (see 5.5).
Spatio-temporal hierarchies

When taking functional hierarchic relationships as a primary criterion it should be stressed that temporal and spatial scales and related hierarchies are extremely important as diagnostic and descriptive tools, but not necessarily decisive in a functional manner. Scales alone are not to be confused up with functional hierarchies, but they delimit their radius of action and relevance. Spatial scales become relevant when larger systems act as a reservoir for other systems for the input of energy, matter or organisms. The larger the source is compared to the dependent system, the more outspoken the hierarchy. Comparison of spatial (or volumetric) scales of functionally related systems can be useful to identify this.

Time scales become relevant when long-term processes, by their rates as well as by their duration, start to dominate short-term processes. It is essential to take into account long-term processes as a background when dealing with proportionally short-term phenomena, an attitude that despite its logic seems to be easily forgotten.

Referring to spatial and temporal hierarchies this could be explained as follows:
- When linking abiotic and/or biotic systems the direction of flows or potential flows of matter and energy (and information) between and through systems is crucial. Flow directions are helpful when deciding which system is dependent on another system. This corresponds with the idea of functional hierarchies between cascading systems. Our approach puts this principle to the fore. Admittedly, there are many cases where flows of matter follow cyclic routes and causal relationships are hard to define. In most cases however the analysis of the flows of energy and the various points in its route, where energy dissipates or is stored (sinks), can help to distinguish between independent and dependent systems. Energy flows direct flows of matter in nearly all cases (Odum, 1983).

- Systems and related phenomena in landscapes have a certain range in spatial extent, and their behaviour (dynamics, lifetime) fits within a certain time frame. They are regarded in their specific spatio-temporal positioning. It is extremely helpful to present systems or related phenomena relative to others in simple diagrams with (logarithmic) scales for time and space (e.g. Odum, 1983; Delcourt & Delcourt, 1988; Hugget, 1991; Urban et al., 1987, O’Neill, 1986, 1988). This helps i) to arrange issues in an order that corresponds with the notions of spatial and temporal hierarchies, ii) to distinguish phenomena by their specific spatio-temporal domain within the same material system and iii) to realize that phenomena in various components of landscapes are either in very different or in comparable domains of temporal and spatial scales and iv) to separate relevant from irrelevant phenomena assessed upon their scale-domains relative to the landscape.

- For our purpose it is assumed that large-scale systems are generally relatively independent and smaller scale systems relatively dependent. This explains why hierarchical concepts emphasize and re-emphasize the importance of scales (e.g. Allen & Hoekstra, 1992). At least within the American school of ecologists, the popularity of hierarchic ‘theory’ gives the impression of a rediscovery of scale. Our study underlines i) the positive effects of such awareness in general ii) the bias of American ecology compared with European (landscape) ecology and iii) the fact that
geographical disciplines did nothing else for most of their time. Conditions for cooperation between ecology and geography are therefore seeming to improve.

5.5 Top-down or bottom-up control of ecosystems?

The question arises whether in nested systems the behaviour of entities at a certain level is conditioned bottom-up (from lower level units upwards) or top-down (from higher level units downwards), or maybe from both sides at the same time? This sometimes leads to conflicting explanations of the same phenomena (see also 3.9).

In many situations, e.g. between trophic levels in an ecosystem, a bottom-up control by lower levels is unquestionable but not necessarily in conflict with a top-down control in exactly the same playing field!

Both mechanisms, affecting the same entities, seem to be paradoxical because there is downward causation and upward causation at the same time. That this behaviour is only seemingly contradictory can be illustrated by using an example from O'Neil (1989) who describes a 'two-way-street-control' in a marine food web. Top-down control of certain species (measured by, e.g. population size) is executed by fish (predator) and these constraints operate on a relatively long-time scale (seasons or longer time units). In the opposite i.e. bottom-up direction, another constraint affects the same subsystem. The latter is related to the availability phytoplankton with its typical intra-seasonal variability in production rates influencing the rest of the food web. Apparently both mechanisms affect the same ecosystem component, but in the opposite directions and with different time-scales.

This stresses the fact that the terrain of hierarchical thinking is not free from semantic traps. The only way to stay away from them is to state clearly which phenomena are being studied and what relationships are being addressed.

5.6 One or more hierarchies at work in landscapes?

The examples given in Chapters 3 and 4 confirmed the variety of processes playing a role in or between subsystems. In concrete landscapes we are dealing with the exchange of organisms between subpopulations in more or less isolated biotopes, with energy-controlled hierarchies in trophic levels, with differences in competitive power, with prey-predator relationships, but equally important is the flow to calcium-enriched groundwater from higher ground to seepage areas, or the frequent occurrence of geomorphological disturbances setting back soil development and vegetation succession. All these processes may respond to general hierarchical principles, but their material content, agents, decision variables, spatio-temporal context, and effects differ considerably. There seems little to gain by forcing them into one 'all purpose hierarchy' a priori and for the sake of theory alone. Our recommendation is that landscape ecological phenomena have to be seen in the context of several different hierarchies.
operating rather separately from each other in the same area. So, adding to our conclusion that hierarchies may well have a certain scale domain, we state that landscapes respond to many hierarchies at the same time (see also O’Neill, 1988, 1989; who suggested a dual hierarchy taking process-functional and organizational aspects into account). One might even go further by splitting up hierarchies into for instance:

- Abiotic
  - cascading subsystems within a compartment (e.g. surface water systems in a drainage network)
  - cascading systems interfacing compartments of different material content (e.g. atmosphere > groundwater > surface water)

- Biotic:
  - biogeographical hierarchies (migration, dispersion)
  - food webs
  - prey-predator relationships
  - competition
  - social structuring

It depends on scientific and practical goals which hierarchy or which combinations we prefer to choose. It also depends on the working scale as such. For instance, interspecies competition offers explanations at a much lower scale domain than climatic constraints. It depends on working scales what to include or what to neglect!

Of course it is necessary to strive for an overall integration of these various hierarchical approaches in order to evaluate their respective weights for defined goal variables.

5.7 Are hierarchies stable, scale-bound and do they allow predictions?

There is sufficient evidence that compound systems, such as ecosystems and landscapes, are likely to display different sorts of functional hierarchies acting synchronously. Science is always in search of predictability, so in relation to predictable behaviour of landscape phenomena it is worthwhile to discover whether (one or more) hierarchical concepts might facilitate our understanding of systems behaviour and therefore allow predictions. Hierarchical ordering could be interpreted as an ordering of constraints in a relatively stable setting of levels. Allen & Hoekstra (1992) emphasize this notion as follows: ‘The question can only be answered to give predictions if the implied scale of system specifications involves a stable ordering of constraints’ ... ‘if what constrains the system is not constant, then predictions are impossible’.

From analyses of energy and matter flows through ecosystems and landscapes a general idea of dependences emerged (see Chapters 2 and 3). It proved possible to arrange systems in a ranking according to their relative dependence and independence, by pairwise comparison, followed by an integration of these insights. Sidestepping necessary specifications per landscape, the picture emerges of a hierarchy that fits most landscapes and is more or less stable. Nevertheless, we have identified domains within or between subsystems where relationships are less asymmetrical (or less hierarchical) and thus less predictable. Examples refer to i) the interaction between atmosphere and oceans and ii) the way well-developed ecosystems show a decrease in abiotic dominance in plant-soil relationships. In most other cases a hierarchical ordering of landscape
phenomena suggests boundary conditions that are more or less stable both in nature and in importance. It also shows that any change in higher level systems (e.g. climate) inevitably results in a change in dependent systems on a lower level.

A related question, referring to discussions raised by, among others Allen & Hoekstra (1992) is whether such a ranking is scale-dependent. If, for example, one declares environmental factors from the abiotic domain to be the independent, constraining party in ecological relationships at landscape level, how about the global level where the biosphere is said to set conditions for abiotic spheres (cf. the Gaia-hypothesis launched by Lovelock, 1979)?

The biosphere regulates radiation, warmth, global cycling of oxygen, carbon dioxide, salt contents in oceans, even the chemical composition of volcanic rock. The atmosphere itself has a chemical composition which is a mockery of thermodynamic equilibria! This certainly supports the idea of a biosphere setting quite a few rules for abiotic spheres and not the other way around. This is a good illustration of the fact that functional hierarchies that express asymmetric relationships are scale-bound. At the same time it is a warning not to extrapolate hierarchies, developed for a certain scale, to completely different scale-domains.

5.8 Why on earth are there hierarchies anyway?

An extremely puzzling question is why hierarchical organization exists anyway. Even purely physical systems in the microcosmos or macrocosmos, such as atomic structures or solar systems, that are hierarchically organized, are difficult to explain. For the, discussion, however, one could find a clue by first looking at the man-made world for analogies. Here, most hierarchies in e.g. administration and our artificial, technical environment were developed for practical, organizational reasons. In fact, hierarchy can be considered to be an organizational principle in the first place (Chapter 2). Why did people come to a solution with several hierarchical levels that seems at first sight more complex, sluggish, time-consuming, indirect, less economical and more expensive than other solutions?

*In man-made systems the key word seems to be ‘overall efficiency’ compensating for drawbacks as listed above. Many hierarchies must have proven abilities in this overall performance which respond to a set of functional criteria. It is relevant to quote Buursink (1975), dealing with the hierarchical ordering of central places (sensu Christaller, 1933) such as larger villages and towns: ‘Hierarchy, a utilitarian form of organization ... is a generally accepted way of organization which clearly shows an element of efficiency. In a hierarchical organization relations between different functions and levels are regulated to procure order. Hierarchy is a means of reaching a certain degree of efficiency in a system’. We took this example to emphasize both the crucial importance of efficiency and, in addition, the fact that this type of ordering is by no means a designed ordering. On the contrary, most of these configurations developed ‘organically’ in close harmony with basic ‘rules’ such as population density, economic carrying capacity, self sufficiency and mobility of persons and goods.*
It is both attractive and speculative to extend this line of thinking by tentatively indicating some essential factors contributing to an overall efficiency in various systems. One could mention for instance economy in the use of energy, materials and manpower, another criterion could be how foolproof systems are or how easy to restore, a next set of criteria could refer to the adaptive abilities in the case of changing conditions, the way individual talents are exploited at various levels and so on. It may well be that certain hierarchies exhibit an overall performance that is better than any other organizational structure that might have better scores on one or a limited set of criteria.

Efficiency as an explanation of hierarchical structure in the man-made world may well be acceptable, it is certainly an anthropocentric and therefore speculative reasoning to extend this to natural phenomena. Even so it is hard to negate striking analogies especially in organizational, ‘nested’ hierarchies in biological systems at all levels. All levels of biological organization such as tissues, organs, individuals, populations, communities and, to a certain degree, ‘mixed’ biotic and abiotic systems (i.e. ecosystems) could be approached as systems with an overall efficiency which has been evolutionarily tested as being foolproof and competitive (see e.g. Milsum, 1972). We could point to the division of ‘labour’ between organs of an individual plant or animal, or - at a higher level - between members of a population, social control constraining individual behaviour for the benefit of the group or the total population and other features dealt with in Chapter 3.

As to the hierarchical ordering of flow directions of energy and matter in abiotic systems, it is definitely questionable whether an inbuilt tendency towards efficiency could be conceived as a leading principle. Abiotic system behaviour cannot be understood from a teleological point of view, at least not in our opinion. The non-nested, cascading or serial configuration of systems representative of a process-functional hierarchy displays a mechanistic response of systems to input of energy and matter from ‘upstream’ systems. This mechanistic behaviour, as found in abiotic systems seems, at first sight to deny any tendency towards a more ‘efficient’ use of energy. However, one can find clues that even in completely abiotic systems there is some ordering or patterns that at least suggests a tendency towards efficiency in transport. The existence of large circulation cells in fluids with energy throughput (ocean gyres, atmospheric circulation cells) or the patterns in stream networks in a drainage-basis, length profile and cross section in a river system could be interpreted as signs that these systems tend to develop a pattern of flow that facilitates the transport of energy or matter (3.6). We concede that all these ‘explanations’ could well be mixed up with a generous dose of teleological thinking just by labelling them in terms of efficiency.

5.9 Hierarchical concepts: a contribution to research economy?

The fact that science finds it difficult to grasp the very core of hierarchical concepts and transform the contents into a neat, well-defined and powerful theory expressed in crisp mathematical formulas, should not lead to an underestimation of their practical
significance. From our experience in this study the following profits are worth mentioning:

- awareness of causes behind causes, or constraints behind constraints going through hierarchical levels enables us to distinguish between the relevant and the irrelevant.

- awareness of the importance of scales in time and space: awareness of system boundaries expressed in space and time helps us to make well-considered choices in research objects, parameters, working scales, delineation of systems.

- identification of the focal level: this also implies insight into patterns and processes on the next higher and next lower level. The choice of the focal level should be based on the expected explanatory power for the phenomena studied. Not all levels have the same score. The level that makes most sense is the so-called coherent level (O'Neill, 1988). In any case, it is worthwhile to go through levels beforehand to estimate which one has most the explanatory power compared with others.

- insight into constraints in (next) higher level(s) offers a better understanding of the behaviour of focal level units. This helps to delineate systems without disregarding external influences, imbedding or 'nesting' them instead of isolating them. This awareness could well be expressed in modelling architecture.
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130


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